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R&T Research & Technology

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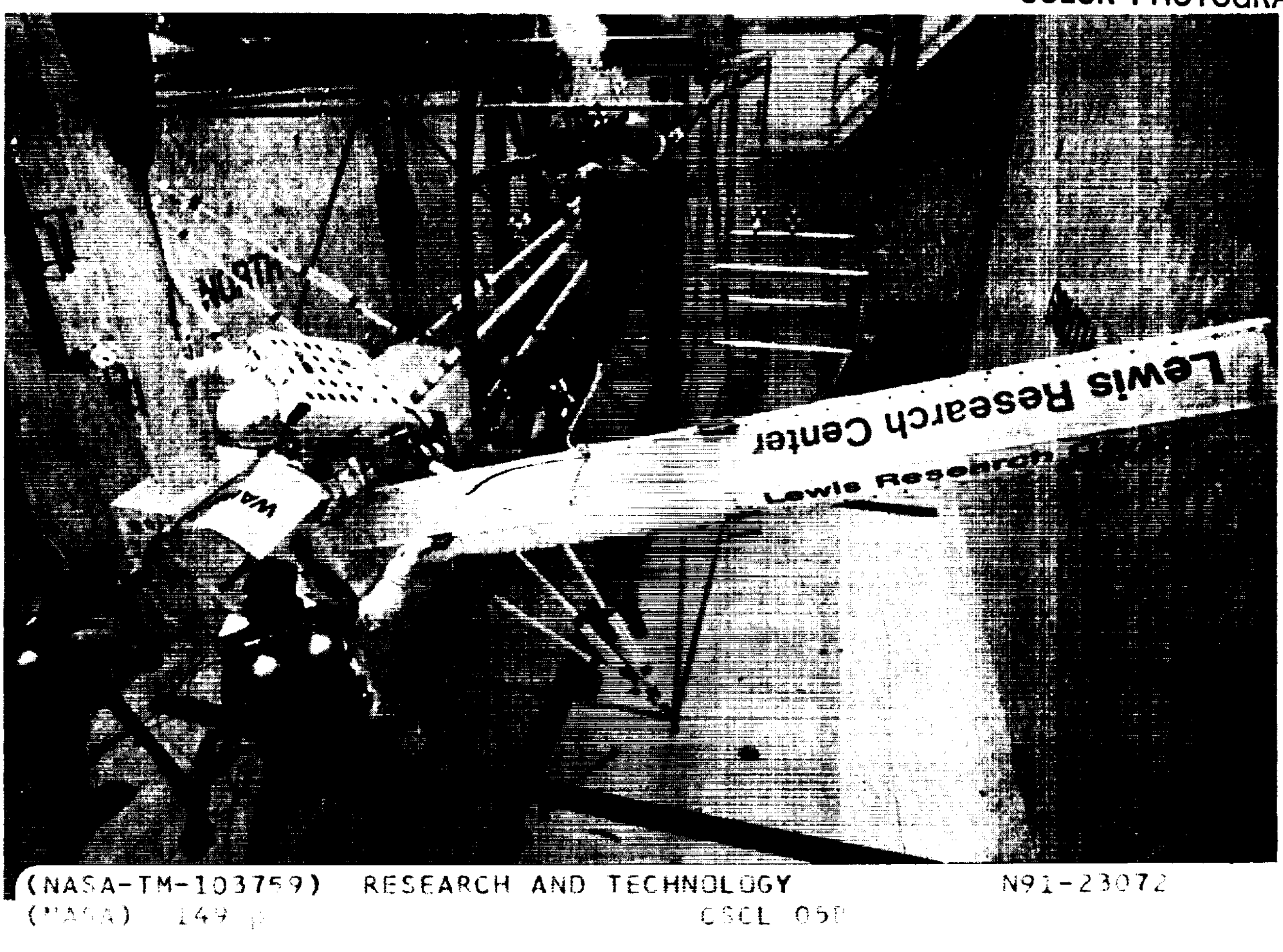

NASA
Lewis Research Center
Cleveland, Ohio

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TECHNICAL MEMORANDUM 103759

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About the cover:

During 1990 the first in a series of Space Station *Freedom* assembly simulations was carried out in the Weightless Environment Test Facility at NASA Johnson Space Center. Through neutral buoyancy testing NASA will produce hardware for *Freedom* Station that can be easily assembled and maintained in space. In this simulated extravehicular activity astronauts are deploying the solar array blanket boxes.

Research & Technology 1990

National Aeronautics and
Space Administration

Lewis Research Center
Cleveland, Ohio 44135

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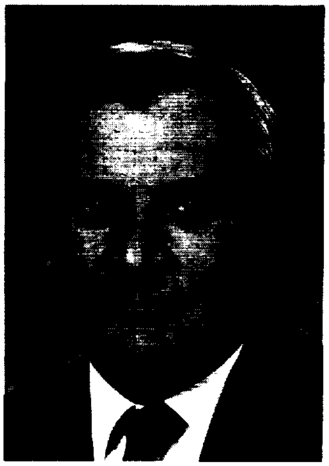

Introduction

The NASA Lewis Research Center is celebrating 50 years of distinguished service to the nation in 1991. A glance through the pages of this report demonstrates the depth and diversity of the programs at Lewis and how far we have come since becoming the NACA Aircraft Engine Research Laboratory in 1941.

The report is organized so that a broad cross section of the community can readily use it. A short introductory paragraph begins each article and will prove to be an invaluable reference tool for the layperson. The more than 100 articles summarize the progress made during the year in various technical areas and portray the technical and administrative support associated with Lewis technology programs. If additional information is desired, the reader is encouraged to contact the authors identified in the articles.

The principal purpose of this report is to give a brief but comprehensive review of the technical accomplishments of the Center during the past year. It is a testimony to the dedication and competence of all the employees, civil servants and contractors, who make up the staff.

The Lewis Research Center is a unique facility, located in an important geographic sector, with a long and distinguished history of performing research and technology development in support of NASA's mission and the nation's needs.

L J Ross

Lawrence J. Ross
Director

Inquiries regarding this report can be addressed to the Office of Interagency and Industry Programs, Mail Stop 7-3. The telephone number is (216) 433-3742 or FTS 297-3742.

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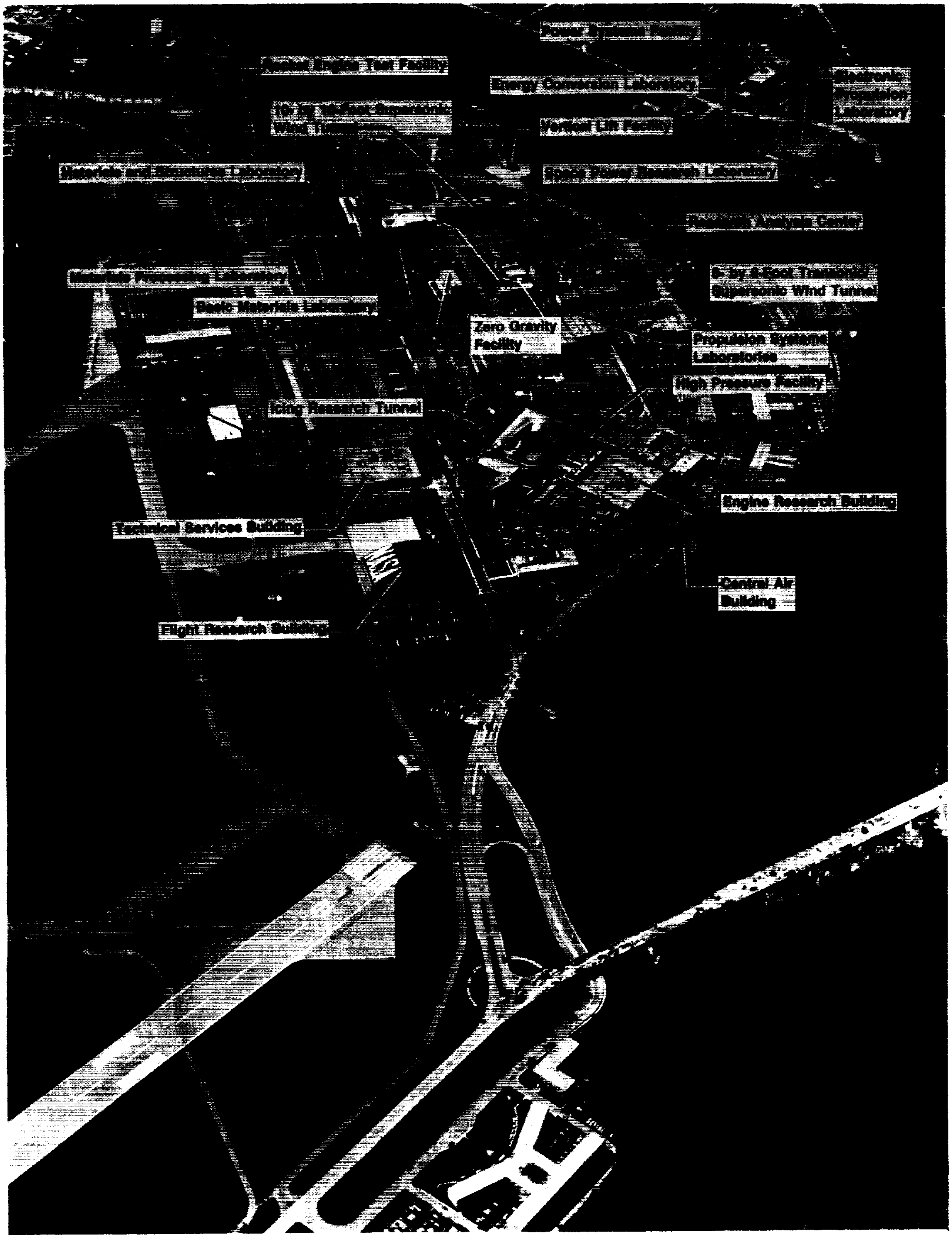

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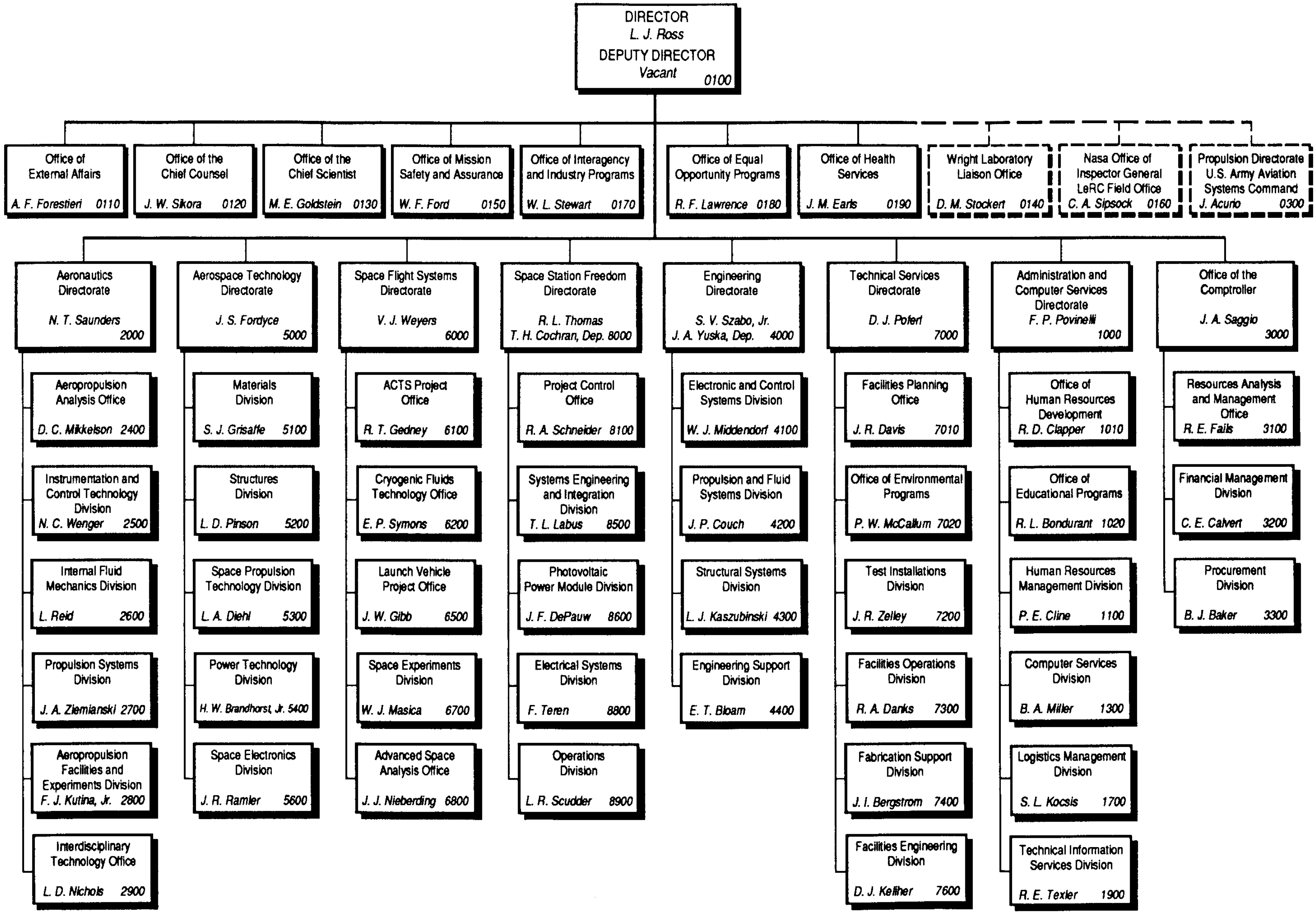

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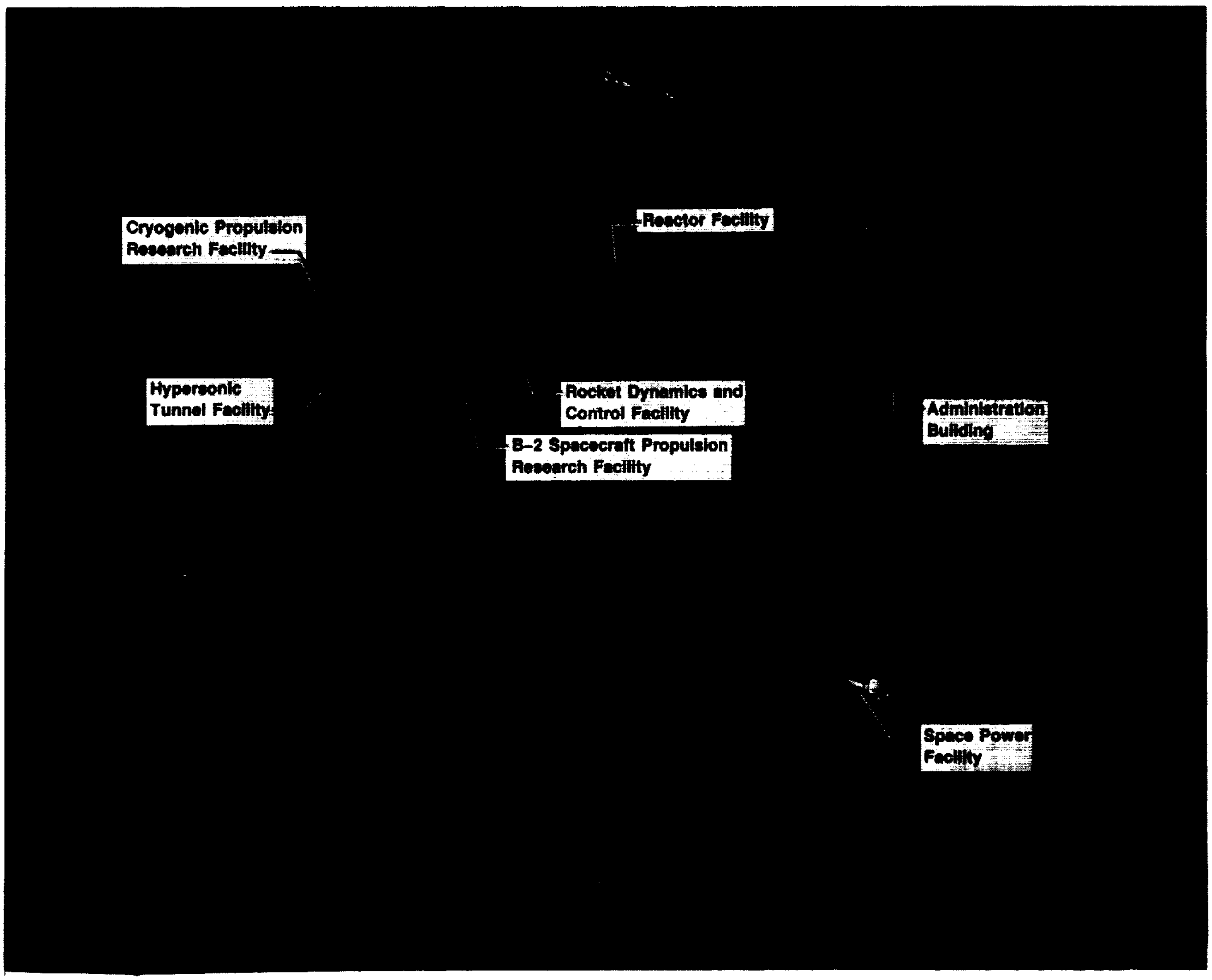

Plum Brook Station, Sandusky, Ohio

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Contents

Aeronautics

Aeropropulsion Analysis

Advanced Core Technology Shows Promise for Subsonic Propulsion

Recent gains in aircraft turbine engine overall efficiency have resulted primarily from the evolution of engines, with higher and higher bypass ratios providing higher propulsive efficiency. Although still-higher bypass ratios can provide some further gains in propulsive efficiency, the potential of using advanced technology in the engine core (i.e., compressor, combustor, and turbine) to provide significant gains in engine performance had not been defined.

Studies were performed by General Electric, Pratt & Whitney, and Allison to assess the potential benefits of advanced core technology in engines suitable for a 500-passenger advanced subsonic transport. Engines based on year 2010 technology were assessed; selected configurations had direct-drive and geared fans that provided bypass ratios of 10 to 25 and overall pressure ratios of 75 to 100 and contained advanced hot-section materials with temperature capabilities of 2500 to 3000 °F. In comparison, current production engines have bypass ratios of 4 to 6, pressure ratios of 25 to 30, and material temperature capabilities of 1800 to 1900 °F.

Reductions in fuel consumption of 20 to 30 percent and in direct operating costs of 6 to 14 percent (at fuel costs of $1 per gallon) were found to be achievable for these engines as compared with engines currently being developed for the near future (1993). The advanced core technologies of higher pressure ratio, improved component efficiencies, and advanced materials directly provide a thermal efficiency gain accounting for 60 percent of the overall performance improvement and also provide the increased power that enables a large part of the propulsive efficiency gain that makes up the remaining 40 percent of the overall improvement. Challenges to achieving this performance potential include developing the advanced core technologies required for performance improvement as well as the small-size combustor technology needed to reduce the emissions resulting from the more severe operating conditions.

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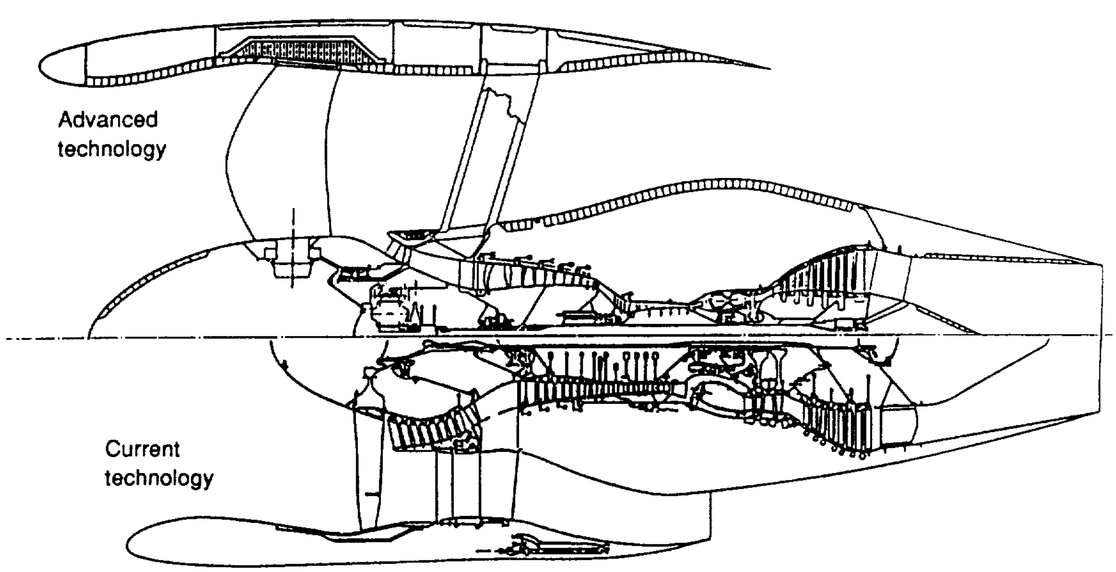
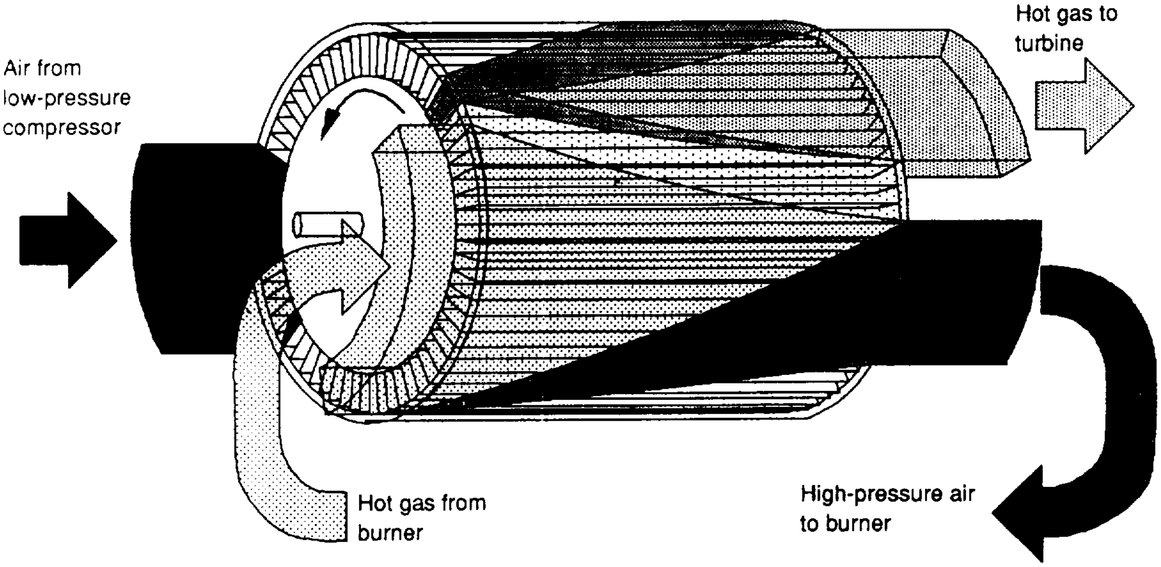


Comparison of advanced-technology and current-technology turbofans.



Simplified drawing of wave rotor.

Wave Rotor May Improve Gas Turbine Core

A considerable amount of gas turbine research today is focused on improving the efficiency of aircraft turbofan engines. One way to achieve high efficiency is by raising the compressor pressure ratio and the combustor temperature significantly above present values (ref. 1). From a conventional aerodynamic and materials standpoint, these tasks are very difficult; however, a new concept that may achieve one or possibly both of these goals is the wave rotor, which is being actively studied here at NASA Lewis.

In the most general sense the wave rotor behaves like a conventional gas turbine. Air enters and is subsequently compressed, heated, and expanded in order to extract useful work. In a wave rotor however, the working fluid gains and loses energy through the use of unsteady, one-dimensional waves instead of conventional rotating airfoils. It has the distinct advantage of effectively concentrating both a compressor and a turbine in one device. A wave rotor might consist of a series of tubes in an annular ring that rotate about an axis parallel to the tubes. As the tubes rotate, the ends of each one are exposed to various ports that create traveling compression or expansion waves and allow the gas within the tube to flow in or out. The key to wave-rotor operation is that the ports are placed such that after they open and create a traveling wave, they close just before any reflected waves or waves from other port openings arrive. Thus, from the point of view of the ports, the flow is completely steady and the waves appear to be stationary. From the perspective of an individual tube however, the waves are moving. The other important aspect of successful operation is that the state of the gas in the tube must be the same at the end of a revolution as at the beginning.

Research at Lewis has concentrated on two major areas. The first is designing a practical cycle. The second is creating a wave-rotor simulation. The simulation developed at Lewis provides information on "off-design" performance as well as on how the wave rotor integrates into a complete engine design.

Reference

1. Glassman, A.J.; Snyder, C.A.; and Knip, G.: Advanced Core Technology: Key to Subsonic Propulsion Benefits. ASME Paper GT-241, June 1989. (Also NASA TM-101420.)

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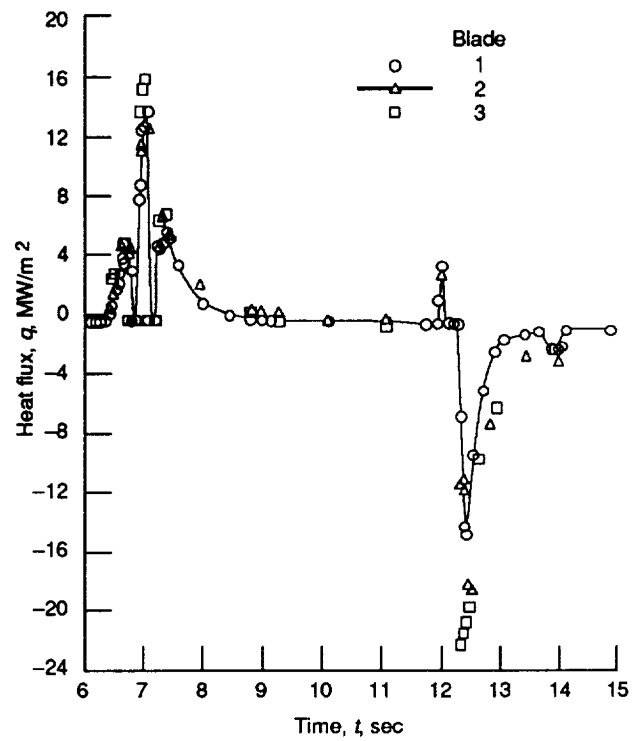
Instrumentation and Controls Technology

New Gage Takes Cyclic Heat Flux Measurements

An improved plug type of heat flux gage has been developed at NASA Lewis. This gage has been used to measure absorbed surface heat flux in a thermal cycling facility located at NASA Marshall Space Flight Center that was designed for testing space shuttle main engine (SSME) turbine blades. This is the first time heat flux has been measured in an SSME turbopump environment. The new concept for the improved gage was developed in a heat flux measurement facility at Lewis.

A complete description of the new heat flux gage is given in reference 1. The full gage length and diameter are nominally 0.12 cm and 0.26 cm, respectively. Temperature-versus-time data generated with thermocouples mounted within the gage are used to determine the absorbed surface heat flux. An inverse heat transfer method incorporating temperature-dependent thermal properties is used to determine transient and quasi-steady-state surface heat flux. This method is based on evaluating heat stored per unit volume (product of material density, specific heat, and measured transient temperature) at each thermocouple location. The gage is defined as thermally thick when the heat stored per unit volume varies greatly along the thermoplug length. This occurs during fast thermal transients. A thermally thin condition occurs during slower thermal transients, when the gradient of stored heat flux is relatively small. These thermally thick and thin gage characteristics are useful in analyzing the heat flux gage performance.

Three instrumented blades were tested in the Marshall facility. The center blade data (solid line in figure) are the most representative of SSME conditions. The peak heat fluxes were measured as 14 and -14.7 MW/m^2 at maximum heating and cooling conditions. These values are in reasonable agreement with SSME design calculations. The experimental heat flux data are used for verification of SSME analytical stress and for boundary layer and heat transfer design models. These peak heat fluxes are 50 to 100 times those encountered in aircraft engines.



Heat flux measurements on three blades.

Future efforts include plans to use these gages for surface heat flux measurement in SSME test-bed engine turbopump nozzles at Marshall, for round-robin heat flux gage testing at Pratt & Whitney and Case Western Reserve University, and for radial turbine rotor, cryogen spray cooling, and thin-film heat flux gage experiments at Lewis.

Reference

1. Liebert, C.H.: Heat Flux Measurement in SSME Turbine Blade Tester. NASA TM-103274, 1990.

Lewis contact: Curt H. Liebert, (216) 433-6483
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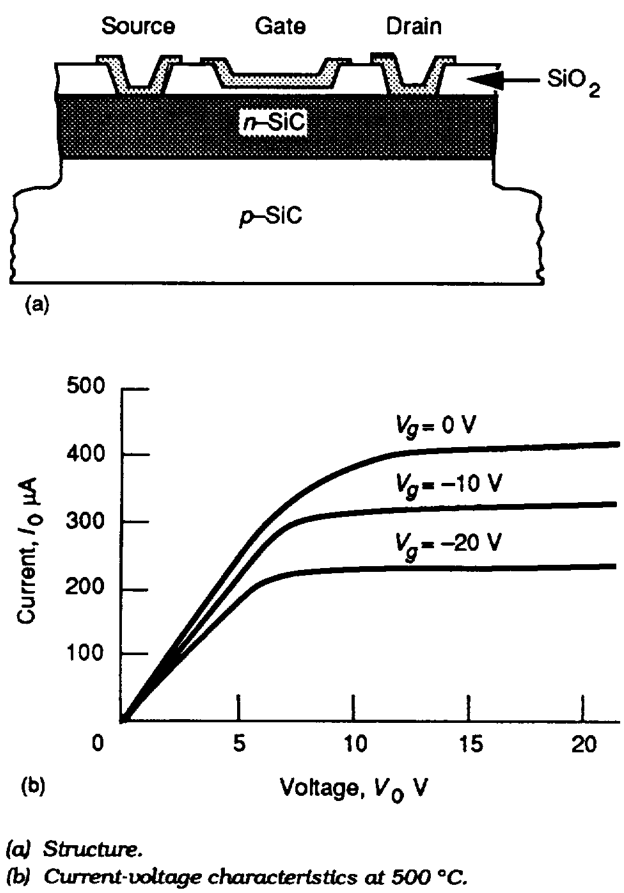
High-Temperature Silicon Carbide MOSFET Operated to 500 °C

The NASA Lewis High Temperature Electronics Program is developing a new family of semiconductor devices based on silicon carbide (SiC). The goal is integrated sensors and electronic devices for operation at 600 °C (and beyond) in aerospace propulsion and power applications. With a chemical vapor deposition (CVD) process developed at Lewis, 6H–SiC single-crystal films are currently being grown on commercially produced 6H–SiC wafers. These films have been used to fabricate a depletion-mode, metal-oxide-semiconductor, field-effect transistor (MOSFET) that has been operated to 500 °C.



(a) Structure.
(b) Current-voltage characteristics at 500 °C.

Device structure and performance at 500 °C of high-temperature, silicon carbide, depletion-mode MOSFET.

The depletion-mode MOSFET's were produced by growing a 0.35-µm-thick *n*-type channel layer on top of a *p*-type isolation layer. Aluminum from trimethylaluminum was incorporated into the growing SiC film during the CVD process to produce *p*-type SiC. An array of MOSFET's was then fabricated by employing photolithography, oxidation, and electrical contact metallization. The electrical contacts—aluminum for the gate contact and gold/tantalum for the source and drain contacts—were applied by sputter deposition.

The current-voltage (I–V) curves in the accompanying figure demonstrate the performance of one of the 6H–SiC MOSFET's at 500 °C. The ideal function of a MOSFET is to operate like a switch. For the *n*-channel, depletion-mode MOSFET, the device is normally on (current flows when the source-to-drain voltage is greater than zero) and is turned off by applying a negative voltage to the gate contact. Owing to nonoptimized oxide and SiC channel thicknesses and channel carrier concentrations, the MOSFET cannot be completely turned off at 500 °C. Nevertheless, obtaining classical MOSFET I–V curves at high temperature is an extremely important accomplishment. It demonstrates that fabrication of field-effect transistors from SiC is feasible. Since the MOSFET is the most basic active electronic device from which integrated circuits can be developed, it is expected that this result will be very important in the development of high-temperature SiC semiconductor technology. Applications in both propulsion and power systems will benefit from this technology.

Future work will be directed toward optimizing the MOSFET structure and fabrication procedures in order to improve the turnoff performance at high temperatures.

Bibliography

1. Powell, J.A.; and Matus, L.G.: Silicon Carbide, A Semiconductor for Space Power Electronics. NASA TM–103655, 1990.

Lewis contact: Dr. J. Anthony Powell, (216) 433–3652
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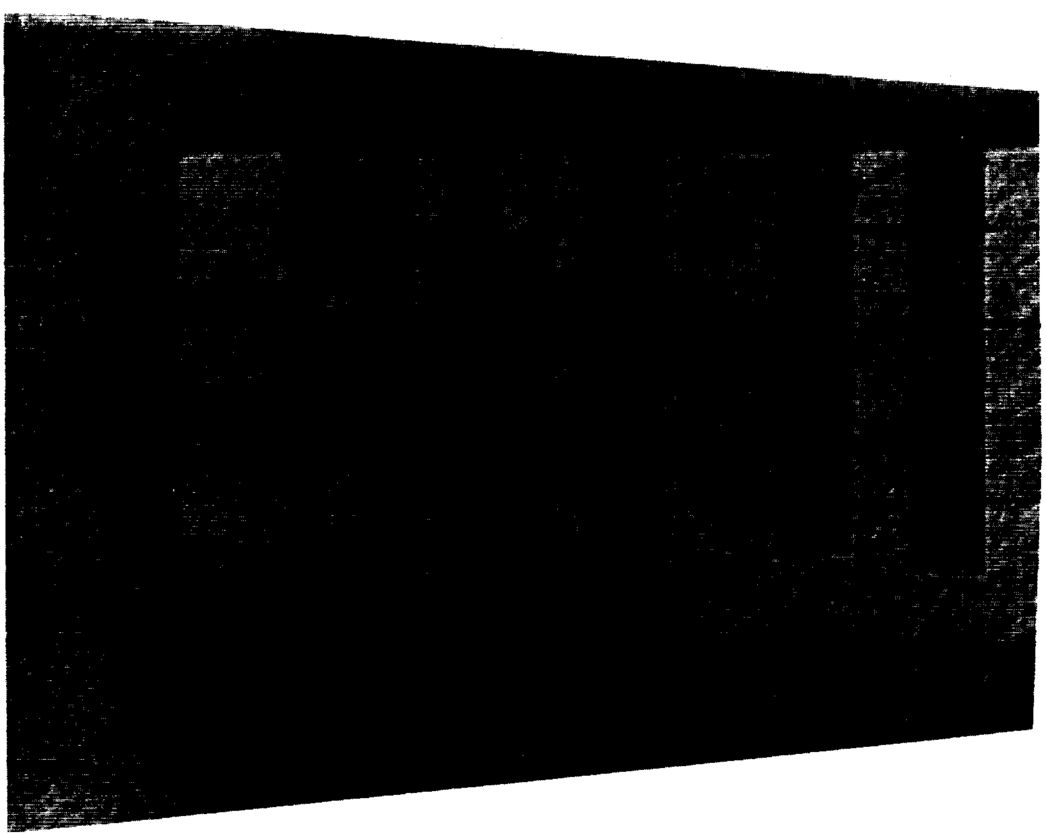
High-Temperature Resistance Static Strain Gage Developed

A high-temperature strain gage that can provide accurate static strain measurements is urgently needed in the development of hypersonic aerospace vehicles and advanced gas turbine engines. The temperatures on the leading edges of the vehicle or the turbine blade may exceed 1000 °C. The requirement for good accuracy at very high temperatures exceeds the present capability of resistance static strain gages, which has generally been limited to 400 °C.

Work at NASA Lewis to develop a high-temperature static strain gage has emphasized the palladium chromium alloy Pd–13-wt%Cr (PdCr). This alloy was selected by United Technologies Research Center (UTRC) under a NASA contract as the most promising material for the high-temperature static strain gage application. It is structurally stable at elevated temperatures and its apparent strain-versus-temperature characteristic is linear, repeatable, and not sensitive to the rates of heating and cooling. However, it has a fairly high (but constant) temperature coefficient of resistance and insufficient oxidation resistance. A temperature compensation technique for minimizing the apparent strain of the gage has been developed as well as an enhanced overcoat for protecting the gage systems from oxidation. Two types of gage are being considered: a wire gage and a thin film gage.

The compensated wire gage developed is made with 25-μm-diameter PdCr wire. The compensator wire is 25-μm-diameter platinum, which is wound around the gage grid. A mixture of alumina and 4- to 6-wt% zirconia (or 1-wt% yttria) is applied to the gage as the protective overcoat. The coated gage has been tested on a Hastelloy-X coupon and an Inconel 718 cantilever beam. The gages are mounted with either ceramic cements or flame-sprayed powders. The cemented gage can be used to approximately 600 °C. At the higher temperatures the porous cement is insufficient to prevent the gage system from oxidizing and shorting to ground. The flame-sprayed gage



A PdCr-based strain gage taped on an Inconel 718 bar.

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works reasonably well to 800 °C, since the flame-spraying technique usually produces a denser film. The change in apparent strain of a prestabilized gage from room temperature to 800 °C is within 300 microstrain, with a reproducibility within 50 microstrain between thermal cycles to 800 °C. The apparent strain of the gage can therefore be corrected to 800 °C because of its repeatability and small value. This is a significant advance over the 400 °C barrier of previous techniques for resistance static strain gages.

The strain sensitivity of this compensated wire gage, both in tension and in compression, is approximately 1.3 at room temperature. The gage responds linearly to the imposed strain to at least ±2000 microstrain. Furthermore, the strain sensitivity of the gage does not vary significantly with temperature.

The sputtered thin-film PdCr gage has a linear and repeatable resistance-versus-temperature characteristic to 1000 °C. This indicates that the maximum use temperature of this thin-film gage can possibly be extended to at least 1000 °C. Work is under way to fabricate a thin-film gage with a compensator element in order to minimize the apparent strain of the gage.

Bibliography

Lei, J.-F.; and Williams, W.D.: PdCr Based High Temperature Static Strain Gage. AIAA Paper 90-5236, Oct. 1990.

Lewis contact: Dr. Jih-Fen Lei, (216) 433-3922
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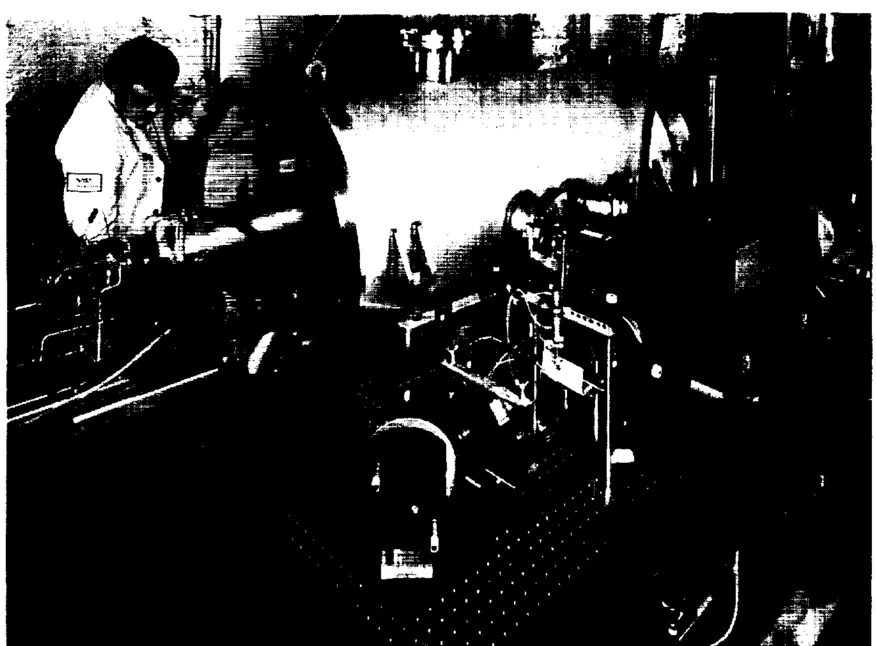
Spectrally Resolved Rayleigh Scattering Diagnostic Developed for Hydrogen-Oxygen Rocket Plume Studies

Nonintrusive measurements of gas density, temperature, and velocity are needed to better understand fundamental flow physics in both aircraft and spacecraft propulsion systems and to provide a data base for validation of new predictive codes. Of the techniques available for these nonintrusive measurements, Rayleigh scattering (i.e., elastic light scattering from molecules) offers several attractive features. The scattering cross section is much larger than that of other techniques, such as spontaneous Raman; no seeding is required; and the equipment is relatively simple. Disadvantages, however, include the need for a flow free of particulates



Rocket test facility and optical configuration for Rayleigh scattering measurements.

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and the need for great care to prevent stray light from reaching the photodetector.

Rayleigh scattering is an elastic process where the internal energy of the scattering molecules is not changed. The spectrum of the scattered light reflects the velocity distribution of the molecules and thus contains information about the thermodynamic parameters. The Rayleigh spectrum is Gaussian for a low-density gas with a Maxwellian velocity distribution. For a single-component gas the width of the spectrum is proportional to the square root of the gas temperature. For a flowing gas the spectrum is shifted by an amount proportional to one component of the mean velocity (in a manner analogous to the Doppler shift). Finally, the total amount of scattered light is directly proportional to the gas density. Thus, the spectrum of Rayleigh scattered light contains sufficient information to determine the thermodynamic state of the gas as well as the mean velocity.

A Rayleigh scattering diagnostic has been developed to measure gas density, temperature, and velocity in the exhaust plume of 25-lb-thrust-class hydrogen/oxygen rockets. The spectrum of argon-ion laser light scattered by the gas molecules in the plume (predominately water vapor) is measured with a scanning Fabry-Perot interferometer. A 1-W argon-ion laser beam (514.5 nm) is passed through an access window into the vacuum chamber and focused at the centerline of the nozzle. A lens is used to collect the Rayleigh scattered light, which is passed through the Fabry-Perot interferometer and detected with a cooled photomultiplier tube. The receiving optics can be moved parallel to the thruster axis, so that the probe volume can be located at any point along the laser beam. Photon counting electronics are used. The spectral data are processed by using a nonlinear least-squares fit to a model function. Estimates of the gas temperature, density, and velocity are obtained along with estimates of the uncertainties in the measurements. In this application, a temperature and a velocity of nominally 1100 K and 4000 m/sec, respectively, were measured.

Bibliography

Seasholtz, R.G.; Zupanc, F.J.; and Schneider, S.J.: Spectrally Resolved Rayleigh Scattering Diagnostic for Hydrogen-Oxygen Rocket Plume Studies. AIAA Paper 91-0462, Jan. 1991.

Lewis contacts: Dr. Richard G. Seasholtz, (216) 433-3754; Frank J. Zupanc, (216) 433-8702; and Dr. Steven J. Schneider, (216) 433-2445
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Internal Fluid Mechanics

Planar Reacting Shear Layer Studied With Laser

Mixing is the heart of combustion—if the fuel and the air are not mixed, the fuel will not burn. Thus, mixing and combustion are interrelated and it is these relationships that we are studying. The basic experiment consists of hydrogen on one side of a splitter plate and heated air on the other; they make contact at the edge of the plate. Mixing is induced by the velocity difference (shear) between the streams, and burning takes place in the shear layer. By using high-intensity laser light, the concentration of the reactants and products can be measured instantaneously (within 4 nsec). The data are gathered by computer. The images (520 × 480 pixels) are observed, averaged, and compared to determine the phenomena occurring.

The experimental data will also be compared with computational (CFD) calculations. This comparison will determine whether statistical turbulent mixing models are adequate to predict mixing with combustion.

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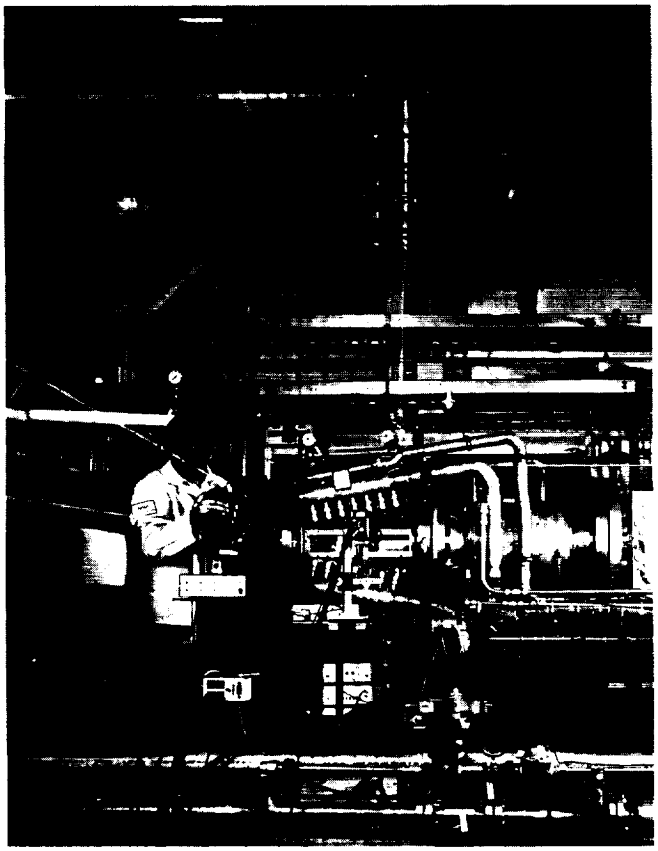

Researcher checking the focusing and alignment of YAG laser.

The photograph shows the high-powered pulse (YAG) laser shining from the laser room along the ceiling to a traversing mirror-lens system and then down through the top of the test section. There are windows on all four sides. An electronic camera from the side of the test section captures the image of the thin mixing plane illuminated by the laser. The laser flashes 30 times per second. In 12 sec enough images are obtained, and either the laser and the camera are moved to a new location in the flow or the flow conditions are changed.

Nonburning images of the mixing wedge and the internal structure of the shear layer will be compared with hydrogen burning images to infer the effect of combustion on mixing.

Bibliography

Wey, C.C., et al.: An Imaging System for PLIF Measurements in a Combusting Flow. NASA TM-103714, 1990.

Marek, C.J., et al.: A Planar Reacting Shear Layer System for the Study of Fluid Dynamics-Combustion Interaction. NASA TM-102422, AVSCOM-TR-89-C-013, Twenty-Third International Symposium on Combustion, Abstracts, The Combustion Institute, July 1990, p. 156.

Wey, C.C.; Ghorashi, B.; and Marek, C.J.: Study of Combustion Processes Through Imaging Techniques. Phase Transport and Particulate Phenomena, Vol. 3, Hemisphere Publishing, 1990, pp. 567-586.

Yu, S.T.; Chang, C.T.; and Marek, C.J.: Modern CFD Applications for the Design of a Reacting Shear Layer Facility. AIAA Paper 91-0577, Jan. 1991. (Also NASA TM-103273.)

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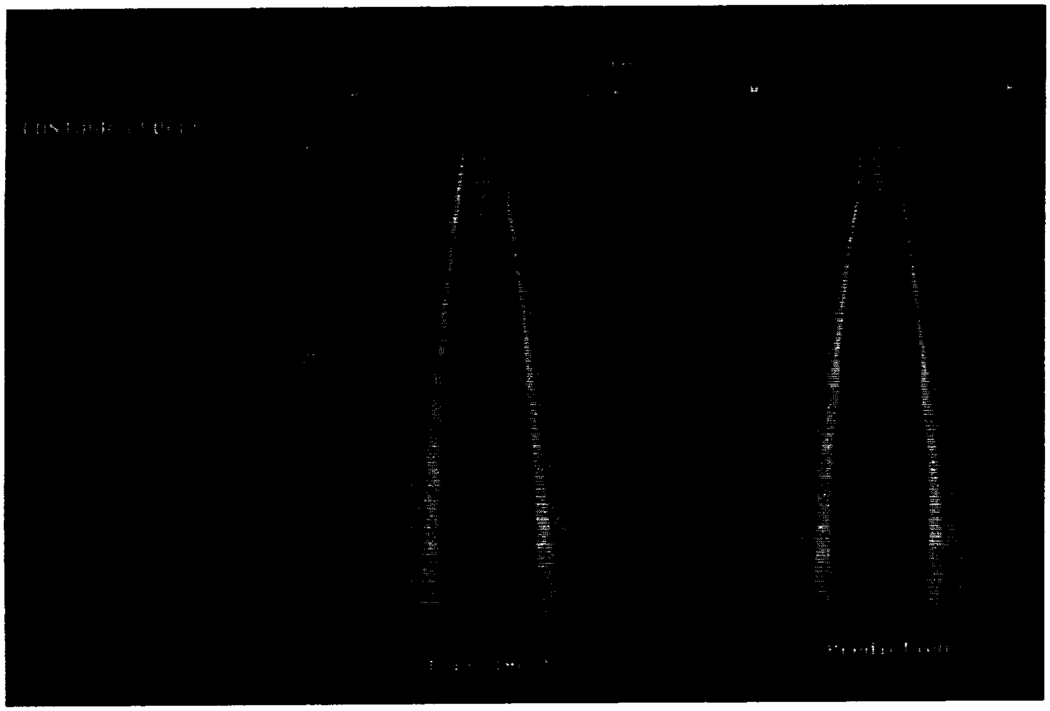
Progress Made Toward Evaluating Multiphase-Flow Computer Codes

In order to demonstrate greater fuel efficiency and higher thrust-to-weight ratios, future engines will be required to operate at higher pressure ratios than current engines. As a result, the injection of liquid fuel into a very dense environment and its subsequent combustion will be a key technology. Computer codes that can accurately simulate this process will be very important design tools.

As a step toward the validation of multiphase computer models, a study of a nonreacting spray was recently completed. Nonintrusive measurements of droplet size and velocity as well as gas-phase velocity were obtained at NASA Lewis for a water spray produced by an air-assist nozzle. The measurements were compared with predictions from a two-phase-flow computer model. It is a separated-flow model that tracks droplet groups through the gas-phase flow field and accounts for momentum exchange between the phases. The model also considers the effects of gas-phase turbulence on droplet trajectories. Predictions were performed under a grant at The University of Illinois at Chicago.

This study is part of an ongoing program in multiphase flows. Currently, unconfined



Comparison of predicted and experimental mean axial droplet velocities for nonreacting spray.

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combusting liquid sprays are being studied. Data obtained in the combusting sprays will allow the evaluation of multiphase-flow computer models, and areas for future code improvement can be identified.

Bibliography

Bulzan, D.L., et al.: Measurements and Predictions of a Liquid Spray From an Air-Assist Nozzle. AIAA Paper 91-0692, Jan. 1991. (Also NASA TM-103640.)

Lewis contact: Dr. Daniel L. Bulzan, (216) 433-5848
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Transition Duct Aerodynamics Studied

A transition duct is an internal flow duct that is characterized by a change in cross-sectional shape along its length. A transition duct of particular interest at NASA Lewis is one that transitions from a circular cross-sectional shape at the inlet to a rectangular cross-sectional shape at the exit. This type of transition duct occurs at the exit of jet engines when a rectangular exhaust nozzle system is required. A rectangular nozzle is desirable for applications involving engine thrust vectoring. The rectangular nozzle shape has the potential for simplifying the variable-geometry mechanisms required for changing the direction of the nozzle thrust vector.

A research program at NASA Lewis is investigating the aerodynamic performance of circular-to-rectangular transition ducts. A key element of the program is an experimental effort designed to provide high-quality flow measurements that can clarify the details of the flow physics within the transition duct and be used to validate and calibrate computational methods. The rectangular-cross-section exit of the particular transition duct being investigated has a width-to-height ratio of 3.0. The length of the duct is equal to 1.5 inlet diameters, and the areas of the duct at the circular inlet and at the rectangular exit are equal.

The transition duct experiments were conducted in the Internal Fluid Mechanics Test Facility. In the design of this facility, special care was taken to condition the transition duct inflow properly in order to provide the desired levels of inflow turbulence, flow angularity, and boundary layer profile. In addition, a swirl generator was designed and built to provide a swirling flow into the transition duct so that the effect of swirl on duct performance could be evaluated. Swirl is an important consideration for nozzle applications because residual swirl from the engine turbine may be present at the transition duct inlet.

Detailed measurements of pressure and the three components of velocity were made at nearly 2000 locations within the transition duct. Results from these measurements indicate a strong influence of the changing geometry on the flow field within the transition duct. The pressure differences generated within the duct as the flow is turned result in the development of vortices at the rectangular exit plane. Adding swirl to the incoming flow dramatically changes the flow field, particularly the development of the vortices.

In addition to this experimental research done at Lewis, complementary research was conducted under grant at The University of Washington. In the Washington experiments, hot-wire anemometry was used to obtain measurements of the unsteady behavior of the flow within the same transition duct geometry.

Bibliography

Reichert, B.A.; Hingst, W.R.; and Okiishi, T.H.: An Experimental Comparison of Non-Swirling and Swirling Flow in a Circular-to-Rectangular Transition Duct. AIAA Paper 91–0342, Jan. 1991.

Davis, D.O.; and Gessner, F.B.: Experimental Investigation of Turbulent Flow Through a Circular-to-Rectangular Transition Duct. AIAA Paper 90–1505, June 1990.

Lewis contact: Bruce A. Reichert, (216) 433–8397
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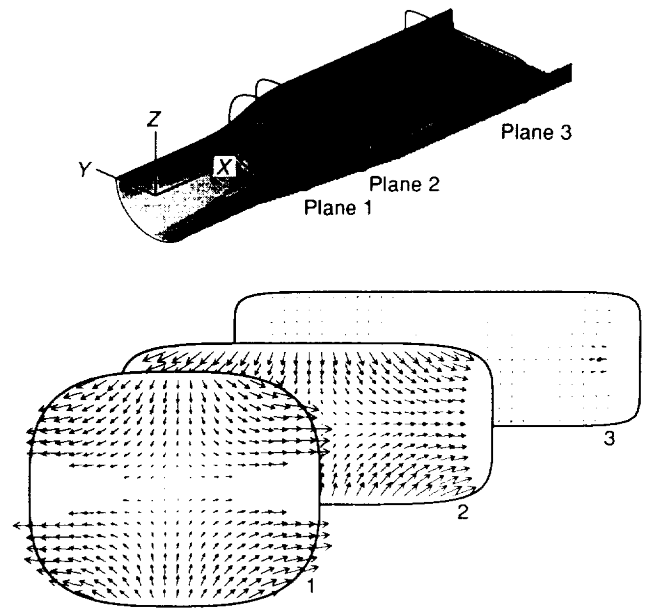
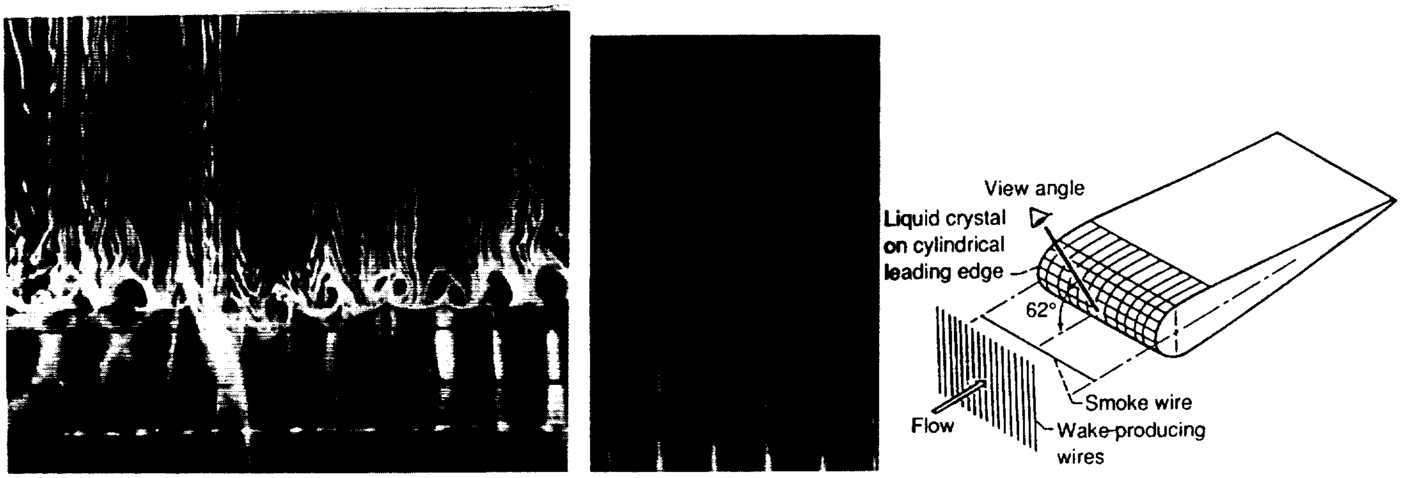


Transition duct velocity measurements.

Stagnation-Region Heat Transfer Increased by Free-Stream Vorticity

The ability to accurately predict the heat transfer to the leading edge of gas turbine blades is very important in designing efficient and reliable engines. NASA Lewis is attempting to determine the mechanism that causes turbulence to increase stagnation-region heat transfer and if the leading-edge geometric profile has an effect on heat transfer.

Smoke wire flow visualization experiments show the flow downstream of an array of fine wires interacting with the stagnation region. The wires produce a velocity gradient that is manifested as a vortex pair in the stagnation region. Liquid crystals on a model of the blade leading edge indicate that heat transfer is a minimum under the vortex pair and a maximum between vortex pairs.



Experiment

Numerical

Stagnation-point heat transfer.

The PARC3D code is being used to develop a numerical simulation of the interaction of the free-stream vorticity with the stagnation region of a circular cylinder and its effect on heat transfer. The numerical results indicate that even if the effects of turbulence are neglected, the spanwise variations in the free stream can cause a substantial increase in the spanwise-averaged heat transfer.

Further experiments and calculations are under way to examine the effect of the geometric profile as well as other flow parameters. The experiment is being performed at NASA Lewis; the numerical calculation is being done by Sverdrup Technology, Inc.

Bibliography

Rigby, D.L.; and Van Fossen, J.G.: Increased Heat Transfer to a Cylindrical Leading Edge due to Small Amplitude Spanwise Variations in the Freestream. AIAA Paper 91-1739, June 1991.

Lewis contact: Dr. James G. Van Fossen, (216) 433-5892
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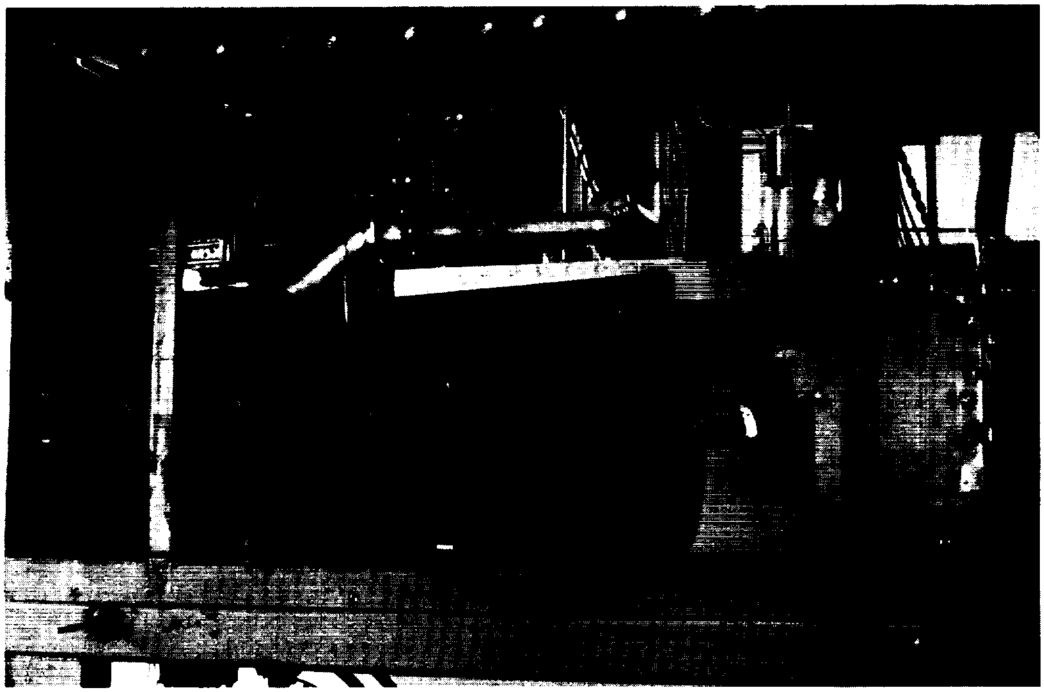
Modified Government Baseline Engine Used for NASP Testing

A hydrogen-fueled ramjet engine model, referred to as the "Government baseline engine," was recently modified extensively to incorporate all of the major engine features of the National Aerospace Plane (NASP) as well as several design options and special instrumentation. A 6-month test of this engine model was conducted by NASA Lewis at the General Applied Science Laboratories Inc. (GASL) to investigate engine operability, dynamics, and performance at Mach 3.5. Improved understanding of engine operability and other significant results were obtained in these recently completed tests.

NASA Lewis used these results to define an inlet configuration that has both excellent starting-restarting characteristics and high performance levels. The data obtained are also being used in the design of a closed-loop engine control system to be evaluated in an upcoming test in the Lewis PSL-4 facility as well as to help designers develop the NASP engine flowpath and control system.

During combustor testing, ignition was achieved by using only a spark ignitor, and stable combustor operation was achieved at



Government baseline engine modified for NASP testing.

the desired high-pressure conditions without unstarting the inlet. Unique operating procedures that included inlet and combustor restart sequences were developed to both start and relight the engine. The effect of an adjacent engine module unstart on engine operation was experimentally evaluated at various operating conditions, and configurations were developed to reduce cross-talk between engine modules and to improve the unstart margin. Engine dynamic response to inlet and fuel flow disturbances was measured for comparison with analyses.

This dynamic response information is now being used in the design of a closed-loop engine control system to be used in an upcoming test in the Lewis PSL-4 test facility. Results of these tests are helping designers develop the NASP engine flowpath and control system.

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Ceramic Components Tested for Gas Turbine Engines

In order to exploit the high-temperature performance potential of the gas turbine engine without using strategic materials or exotic hot-section cooling techniques, NASA Lewis is working to develop a ceramic component technology base. As part of the U.S. Department of Energy's Automotive Gas Turbine Program, the Advanced Turbine Technology Applications Project (ATTAP) is developing structural ceramic hot-flow-path component technology for advanced small gas turbine engines. These engines, designed to operate at temperatures to 2500 °F, have the potential for significantly less fuel consumption than either metal turbine engines or conventional piston engines. In addition, the turbine engines operate with reduced emission levels that meet the current and proposed Federal standards.

Technology development contracts are in place with the Allison Gas Turbine Division of

General Motors and with the Garrett Auxiliary Power Division of the Allied-Signal Aerospace Company. Each contract relies on the strong support of the U.S. ceramics industry for component development.

During the past year good progress has been made in applying the improved monolithic ceramic materials and processes to the fabrication of engine quality components. Fabrication trials demonstrated in-component material strengths and dimensional quality that meet engine specifications.

Allison and Garrett have received the first of the ATTAP-developed ceramic components that were judged to be of engine quality. Cold-flow tests, at Allison, of a gasifier turbine scroll and vane assembly indicate that the ceramic parts meet aerodynamic flow and leakage parameters specified in the design analyses. The ceramic parts are now being prepared for rig and test-bed engine testing at temperatures up to 2500 °F.

Ceramic component design improvements are currently being made. Design changes will address improved fabricability, increased process yield, and component survivability.

Bibliography

Kidwell, J.R.; Lindberg, L.J.; and Morey, R.E.: ATTAP/AGT101—Year 2, Progress in Ceramic Technology Development. ASME Paper 90-GT-305, June 1990.

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Low-NO_x Combustors Show Promise

Control of oxides of nitrogen (NO_x) produced by aircraft flying in the stratosphere has been identified as the top priority in High Speed Research (HSR) studies conducted at NASA Lewis, Boeing, and McDonnell Douglas. In the stratosphere, at altitudes of approximately 50,000 ft and above, NO_x acts as a catalyst to destroy ozone. In order to build an environmentally acceptable High Speed Civil Transport (HSCT), NO_x emissions must be reduced. The goal NO_x levels (3 to 8 grams of NO_x per kilogram of fuel consumed) represent approximately 90 percent reductions of the NO_x levels produced by conventional combustion systems.

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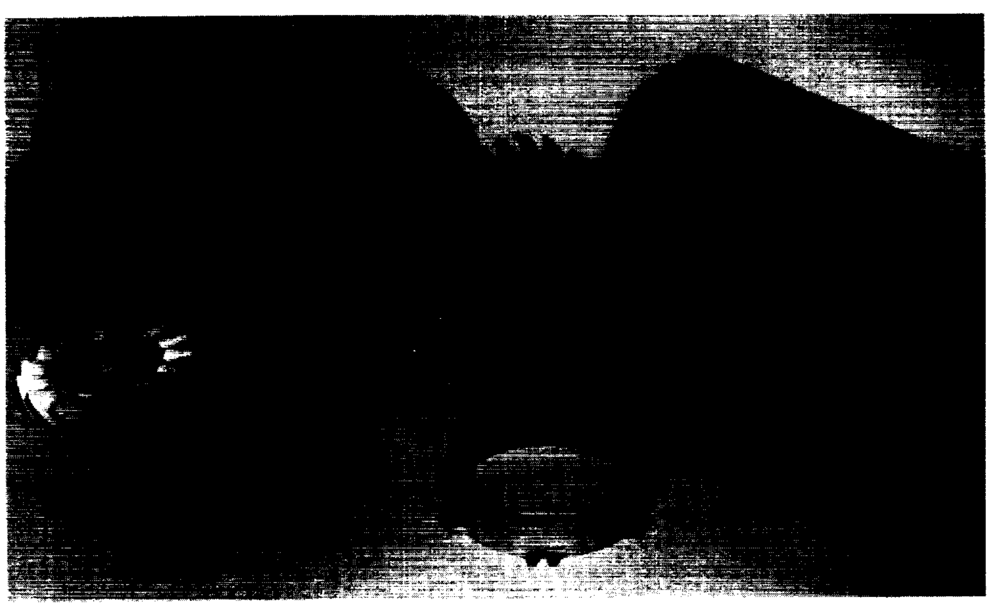

ATTAP ceramic components.

An extensive program to reduce NO_x in gas turbine combustors is under way at Lewis. In-house experiments are planned to provide evidence of the feasibility of two promising combustor concepts: lean premixed pre-vaporized (LPP) combustion, and rich burn/quick quench/lean burn (RQL) combustion.

The LPP concept is based on burning at a lean fuel/air ratio, where the mixture has less fuel than at the stoichiometric fuel/air ratio (when fuel and air are in "perfect balance" so that all the fuel burns with all the oxygen in the air). A lean mixture burns at a lower flame temperature and produces lower NO_x emissions. The LPP combustion flame tube rig is currently in operation. NO_x levels within the HSR goal range have been obtained. Further testing at higher inlet temperatures and pressures is planned. Detailed studies of the fuel injection system and combustion chemistry (using laser diagnostics) will follow the initial combustion tests.

The RQL concept uses the principle that both rich (greater fuel/air ratio than stoichiometric) and lean mixtures produce lower NO_x. Rich combustion is more stable but uses more fuel than necessary. Therefore, a staged combustor concept is envisioned where the stable rich zone is followed by a "quick quench" zone to pass quickly through the stoichiometric condition to a lean burning chamber, which completes the burning process. The RQL combustion flame tube rig is currently being installed.

Contracted work is also being done to develop these concepts into actual combustors for use in the future HSCT. General Electric is concentrating on the LPP combustor concept, and Pratt & Whitney is focusing on the RQL combustor. Many university grants complement the overall program. Some grants are providing analytical support that assists in the prediction of combustion processes at the HSR conditions. Some university grants are developing laser diagnostic capabilities for making nonintrusive measurements in the LPP and RQL combustion test rigs.

Bibliography

Nguyen, H.L.; Bittker, D.A.; and Niedzwiecki, R.W.: Investigation of Low NO_x Staged Combustor Concept in High-Speed Civil Transport Engines. AIAA Paper 89-2942, July 1989. (Also NASA TM-101977.)

Tacina, R.R.: Combustor Technology for Future Aircraft. AIAA Paper 90-2400, July 1990. (Also NASA TM-103268.)

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Advanced Low-Power Deicing Systems Tested in Lewis Icing Research Tunnel

NASA, the U.S. Air Force, and industry have conducted a joint test program to develop a data base that characterizes the performance of advanced, low-power deicing systems. This was the first such study that attempted to put all the currently available systems on a common basis.

Six companies provided a total of eight different deicing systems. The systems used pneumatic or electromechanical impulses (either eddy current repulsive or electro-expulsive methods) that cracked, debonded, and expelled the ice. Aerodynamic forces also contributed to the ice removal process. The systems ranged in developmental maturation from those that had undergone only limited ice tunnel testing to those that were near the certification stage. Some had been flight tested in icing conditions.

This work is driven by the need to find acceptable alternatives to the hot gas bleed anti-icing systems conventionally used on large jet aircraft. Bleed air for anti-icing has

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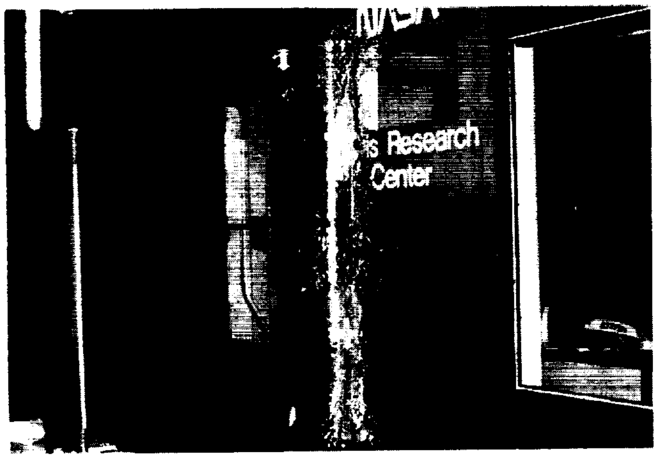

Eddy current repulsion deicer strip removing ice during testing.

become scarce on advanced turbofan engines because they have smaller core flows than the earlier, less efficient engines. Although electrically powered thermal anti-icing systems are available, their applicability is restricted because of their high power draw. Anti-icing systems prevent any ice from forming on a surface. Deicing systems allow ice to build to some predetermined thickness before the deicer is actuated. Thus, although the deicing systems require substantially lower power than the anti-icing systems, they impose an aerodynamic penalty caused both by the ice that builds up before actuation and by any residual ice that remains after actuation. When deicers are used on engine inlets, the engine must be capable of ingesting the shed ice without sustaining damage to the fan blades or other components in the engine.

In order to characterize the low-power deicers, three parameters were measured during the testing in the NASA Lewis Icing Research Tunnel: (1) ice removal effectiveness (i.e., area coverage and thickness or size of the residual ice particles), (2) size or mass of shed ice particles, and (3) weight and power required to operate the deicer. The required power per unit area for these advanced deicers was found to be about one-tenth to one-twentieth of that for anti-icers.

High-speed videography was used to capture ice shedding events and to obtain quantitative measurements on the maximum size of shed ice particles for various time intervals between deicer actuations.

The results of this test program will be presented to representatives of industry and Government at the USAF/NASA Joint Low Power Deicing Conference on February 11-13, 1991, at Tinker Air Force Base, Oklahoma City, Oklahoma, under the sponsorship of the USAF Air Logistics Command.

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Computer Numerically Controlled Grinding Speeds Production of Spiral Bevel Gears

The aerospace gear manufacturing community faces many problems when producing aircraft-quality gears. Short production runs and extremely tight tolerances require continuous changes in machine settings by highly skilled machine operators. These problems are even more troublesome for the manufacture of spiral bevel gears. Current manufacturing machinery requires all adjustments to be completed manually. Changing the machine to manufacture a different gear design requires long setup times. These production problems led to this project for improving spiral bevel gear manufacture through application of computer numerical control (CNC). The spiral bevel gear grinding machinery was converted where appropriate to CNC. The addition of CNC shortened setup and production times and thus reduced costs.

The program was conducted under a NASA contract with funding provided by the U.S. Army Aviation Systems Command and with Bell Helicopter Textron Inc. as the prime contractor and the Gleason Works as the major subcontractor. The program was completed in three phases. Phase one involved the design of the prototype CNC grinder based on the #463 Gleason manual grinder. Phase two entailed rebuilding a Government-owned #463 manual grinder and adding the CNC machine improvements. Phase three was the production testing of the prototype machine at Bell Helicopter. During a series of nine tests the average savings on setup time and grind cycle time were 65 and

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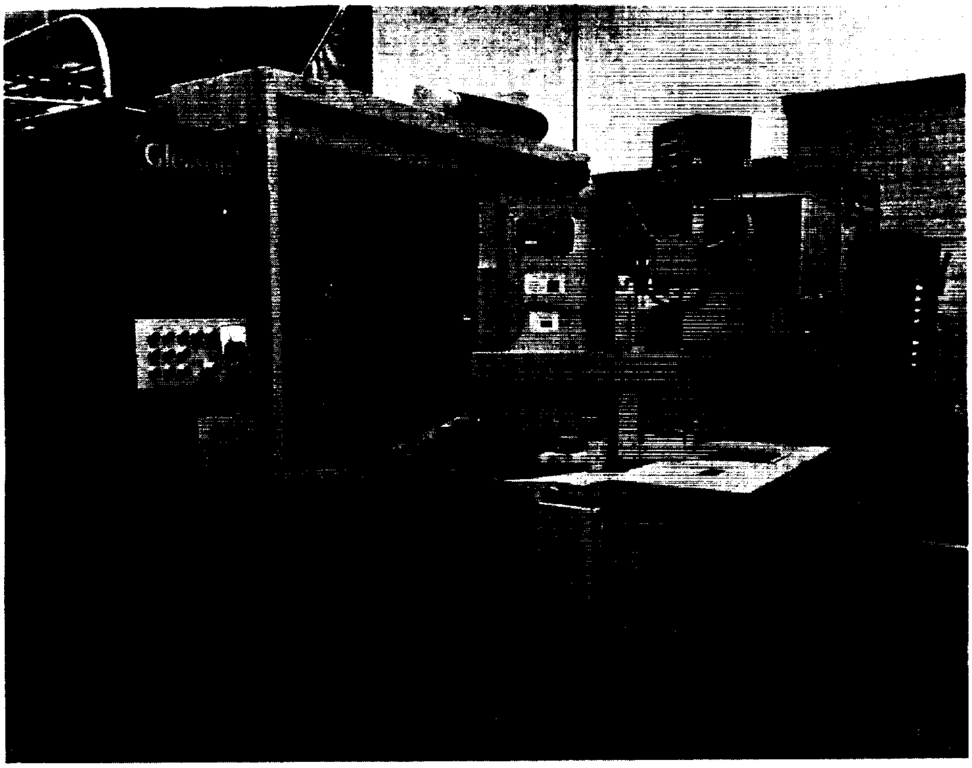

Computer numerically controlled spiral bevel gear grinder.

34 percent, respectively. The program was completed in March 1990.

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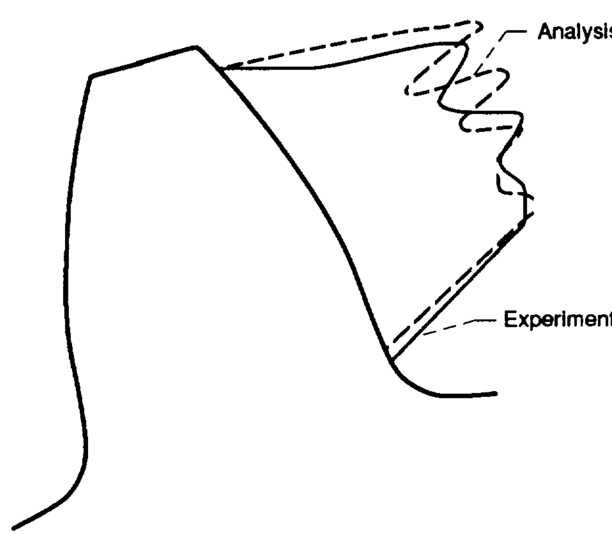
Gear Dynamics Code Validated

Helicopter cabin noise levels are too high, often exceeding 100 dB. A major source of this noise is vibration generated by the gearbox and transmitted to the airframe. Gear vibration is caused primarily by the abrupt transition of the load from tooth to tooth as gears mesh. Modifications to gear tooth profiles can be used to smooth this dynamic action. A NASA/U.S. Army research project has sponsored development of gear dynamics computer codes to help design quieter gears. Gear dynamics experiments to verify these codes were performed in the NASA Lewis Gear Noise Facility.

An instrumented gearbox was tested under a range of speeds and loads to obtain experimental data with which to validate the gear dynamics code DANST. Miniature strain gages mounted on gear teeth were used to measure the dynamic force acting between the teeth. A typical time history comparing the measured and predicted dynamic loads on a



Gear tooth dynamic load.

gear tooth is shown in the figure. The similarity of the waveforms indicates that the analysis does simulate the physical behavior of the test gears. The maximum dynamic load predicted generally agreed with experimental results within 6 percent for the 28 test conditions studied.

The validated code will allow gear designers to tune gear profiles for minimum values of dynamic load, stress, noise, and vibration without expensive and time-consuming hardware testing. Experiments continue to extend the range of application of DANST and to validate other dynamics codes.

Bibliography

Oswald, F.B., et al.: Comparison of Analysis and Experiment for Dynamics of Low Contact Ratio Spur Gears. NASA TM-103232, 1991.

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Hot-Gas Ingestion Tests Performed

Advanced short takeoff and vertical landing (STOVL) aircraft are being considered for operation around the turn of the century. In order to meet this target, the technologies critical to the successful operation of STOVL concepts must be resolved. One of the critical technologies associated with the vertical-lift concept is that of hot-gas ingestion while the aircraft is near the ground as in the takeoff, hover, and landing modes: When hot engine exhaust gas impinges on the ground and radiates forward, a portion of this gas may be ingested by the engine inlet. Once this occurs, the hot gas can have a significant effect on engine stability and performance and aircraft control.

In an ongoing in-house NASA Lewis program, accomplished with the participation of McDonnell Douglas, the engine inlet for a 9.2-percent-scale STOVL model was tested for ground effects. This model was installed in the Lewis 9- by 15-Foot Low Speed Wind Tunnel, which has a unique capability that allows the remote, automated positioning of test hardware. Furthermore, the facility has a sheet laser illumination system to document the complex flow phenomena associated with hot-gas ingestion.

As a result of the test program an extensive data base for in-depth understanding of hot-gas ingestion has been acquired. Data were obtained at simulated exhaust gas temperatures to 1000 °F, and an extensive airflow visualization data base was produced. The data will be used to improve empirical techniques for predicting hot-gas ingestion, so that future STOVL aircraft concepts can be screened during preliminary design, and to validate computational prediction methods.

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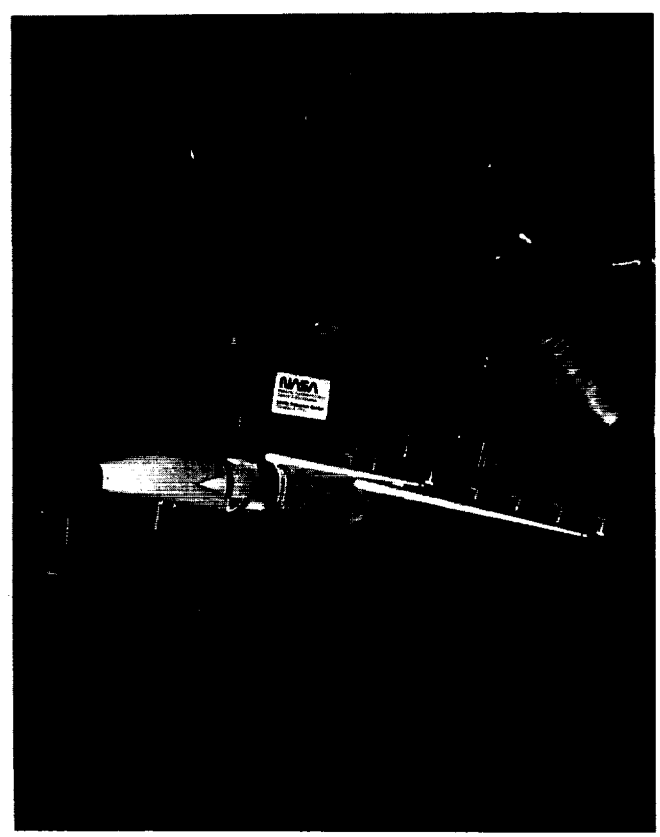
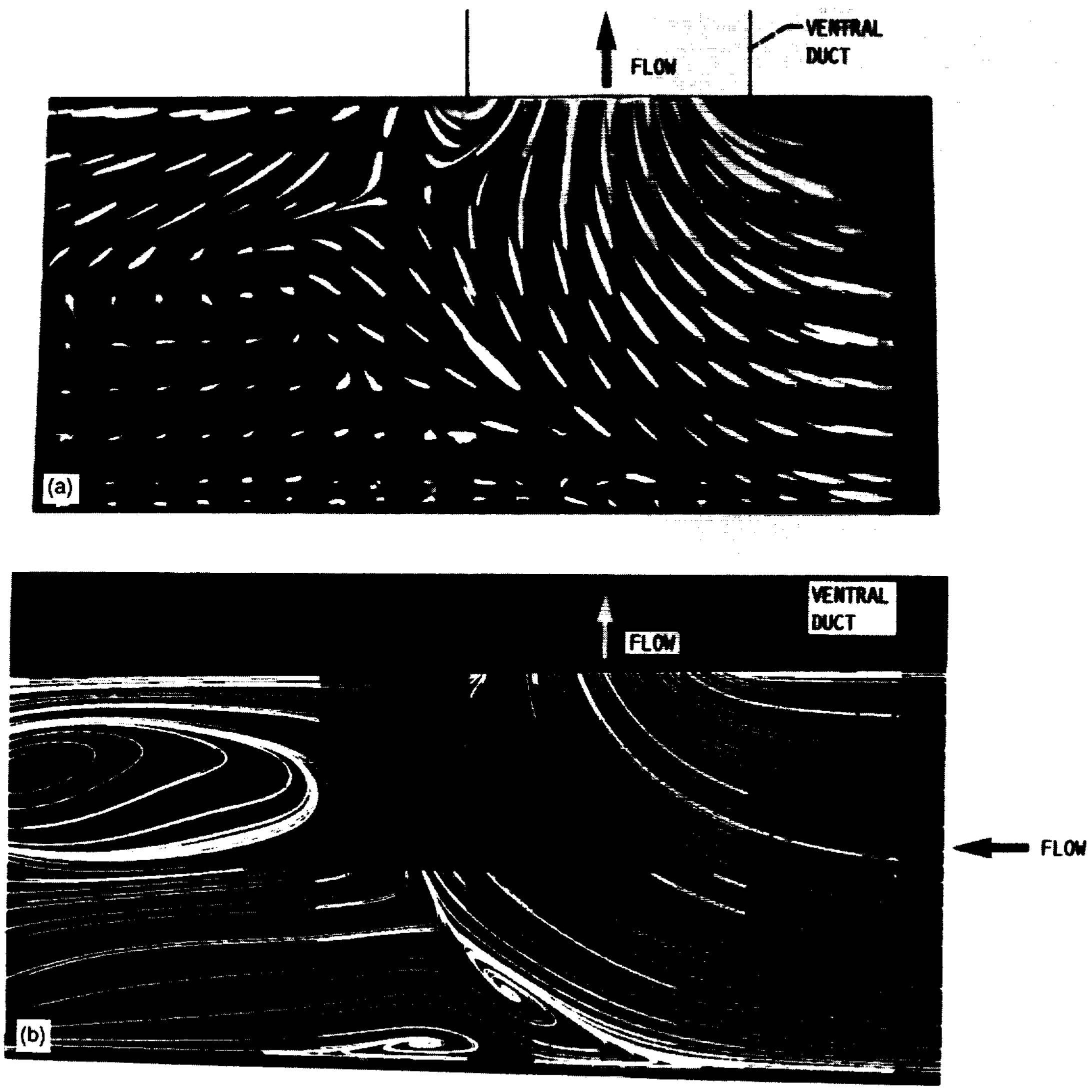


STOVL model in wind tunnel.

Study of Ventral Nozzles Completed

Improved short takeoff and vertical landing (STOVL) aircraft are planned for possible future development. For these aircraft the same propulsion system will provide power for lift and hover as well as for supersonic horizontal flight. When the STOVL propulsion system is operating in the lift mode, the rear jet nozzle will be blocked, and valves will be opened to duct engine exhaust gases to two or more thrusters directed downward. In many proposed configurations one of the lift thrusters will be a ventral nozzle located in the bottom of the aircraft fuselage. To develop the required technology for these aircraft, NASA Lewis is conducting an ongoing, in-house effort on vertical-lift thrust nozzles.

One major objective of the overall STOVL research program is to establish aerodynamic design principles and a data base for vertical-lift components through experimental testing and computational fluid dynamics (CFD) analyses. Experimental and analytical flow studies of the same generic model tailpipe and ventral nozzle have recently been completed. The model was about one-third of full size, and the end was closed to simulate a blocked exhaust nozzle, a typical configuration during



(a) Experiment.
(b) Prediction.

Results of ventral nozzle flow studies.

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the vertical-lift mode. The analytical work was done by using PARC3D, a full Navier-Stokes CFD code, on a Cray supercomputer to predict the internal flow patterns and overall ventral system performance.

The modeling technique and the PARC3D computational code did an excellent job of analytically predicting internal flow patterns and system performance. Solutions were obtained for two computational grid densities (i.e., coarse and fine flow area definition). The finer grid solution produced more detailed flow patterns and predicted performance parameters, such as thrust and flow coefficients, within 1 percent of the measured values, but the coarse grid solution required less computer time. As a result, a calibrated CFD analytical tool (PARC3D) is now available to assist in designing STOVL propulsion ventral nozzles.

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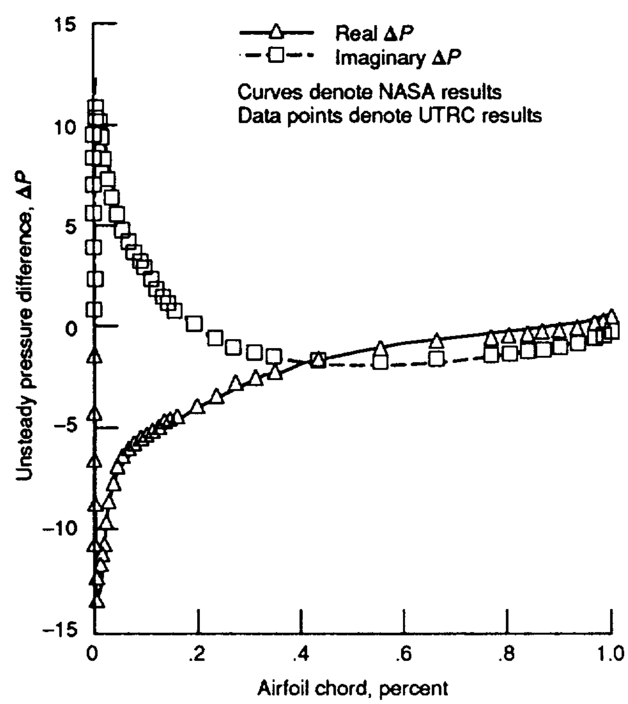
Steady Solver Developed for Analyzing a Cascade of Airfoils

Recent trends in the design of blading for turbomachinery and turboprop applications have been toward lighter blades, higher tip speeds, and increased blade loading. These trends have resulted in greater emphasis on understanding unsteady flow phenomena associated with noise generation and aeroelastic response. Presently, classical, unsteady linearization theory together with empirical corrections form the bases for most aeroelastic prediction systems. However, classical linearization techniques formally apply only to flat-plate airfoils, which are representative of lightly loaded blades. In addition, the trends to higher steady blade loading and tip speeds have placed a strain on the empirical corrections needed for these flat-plate predictions. As a result, recent developments in unsteady aerodynamic models have focused on techniques that account for important design features, such as real blade geometry, mean blade loading, and operations at transonic Mach numbers.

The need to assess the aeroelastic and aeroacoustic response of a propulsion system early in the design phase has resulted in a requirement for unsteady aerodynamic models that are accurate and numerically efficient. One such model is the two-dimensional, linearized, inviscid flow analysis developed by Verdon at the United Technologies Research Center (UTRC). This model assumes that the unsteady flow can be represented as a perturbation of the underlying nonuniform mean flow. In this manner the effect of real blade geometry and loading on the unsteady aerodynamic response is taken into account. Thus, in order to predict the unsteady aerodynamic response of a cascade with this technique, the steady flow field must first be calculated.

A full potential steady flow solver has been developed explicitly for use with the unsteady model of Verdon and Casper. The solver uses the nonconservative form of the nonlinear potential flow equations together with an implicit, least-squares, finite-difference approximation to solve for the steady flow field. The difference equations are developed on a composite mesh that consists of a polar



Unsteady pressure difference for a two-dimensional cascade of airfoils in torsional oscillation about their midchord.

type of local C-mesh for the leading-edge region embedded in a rectilinear type of cascade mesh. The composite mesh is capable of resolving blade-to-blade and far-field phenomena on the rectilinear mesh while accurately resolving local phenomena on the polar mesh. The resulting system of equations is solved by using a Newton iteration technique.

The steady solver, in conjunction with the linearized unsteady flow model, has been verified by comparing it with unsteady results obtained at UTRC. The steady flow field used for the UTRC calculations was obtained by using a proprietary design code. The test case consisted of a cascade of airfoils obtained by using a NACA thickness distribution superimposed on a circular-arc camber line. The particular airfoil had a thickness-to-chord ratio of 0.06 and a camber line midchord height of 0.05. The cascade had a stagger angle of 45° and a solidity of 1.0. The inlet velocity was Mach 0.7 at an incidence angle of 10°. The figure shows the real (in phase) and imaginary (out of phase) components of the unsteady pressure resulting from torsional motion about the midchord with an interblade phase angle of 180° and a reduced frequency of 1.0. The agreement between the NASA and UTRC results is quite good. Comparisons have also been made with steady and unsteady experimental data obtained from an oscillating cascade; again good agreement was obtained.

Development of the steady solver is continuing with the addition of shock-capturing capabilities so that flows at transonic Mach numbers can be analyzed.

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Grid Generation Program Models Complex Geometries

Work is continuing to improve the analyst's ability to predict the internal coolant flow in cooled turbine blades. One step needed to make multidimensional coolant flow calculations is to model the complex geometry of cooling flow passages with grids for numerical calculations. A software package, GRID2D/3D, was developed for this purpose. GRID2D/3D is an efficient and user-friendly computer program for generating grid systems within geometrically complex two- and three-dimensional (2D and 3D) spatial domains. Grid systems generated by GRID2D/3D can be used with finite-difference or finite-volume methods to analyze fluid flow, heat transfer, and combustion problems in arbitrary-shaped geometries.

GRID2D/3D generates grid systems by using an algebraic method that employs an interpolation scheme to control the distribution of grid points. All grid systems generated can have grid lines that are continuous and differentiable everywhere up to the second order. Also, grid lines can intersect boundaries orthogonally. Different grid systems generated by GRID2D/3D can be patched together to form new grid systems. In this way, very elaborate grid systems can be constructed for very complex-shaped geometries.

GRID2D/3D contains a graphics package for evaluating the grid systems generated. With the graphics package, users can generate grid systems in an interactive manner with the grid generation part of GRID2D/3D.

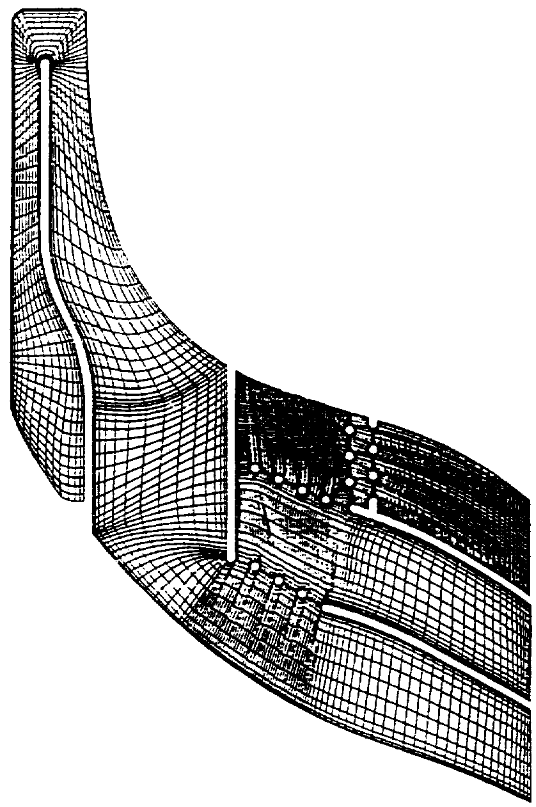
GRID2D/3D is written in FORTRAN 77 and can be run on any IBM PC, XT, or AT compatible computer. In order to use GRID2D/3D on workstations or mainframe computers, some minor modifications must be made in the graphics part of the program; no modifications are needed in the grid generation part of the program.

Bibliography

Shih, T.I-P., et al.: GRID2D/3D—A Computer Program for Generating Grid Systems in Complex-Shaped Two- and Three-Dimensional Spatial Domains; Part 1—Theory and Method. NASA TM-102453, 1990.

Bailey, R.T., et al.: GRID2D/3D—A Computer Program for Generating Grid Systems in Complex-Shaped Two- and Three-Dimensional Spatial Domains; Part 2—User's Manual and Program Listing. NASA TM-102454, 1990.

Steinthorsson, E.; Shih, T.I-P.; and Roelke, R.J.: GRID2D/3D—A Computer Program for Generating



Blade coolant passage model created with GRID2D/3D.

Grid Systems in Complex-Shaped Two- and Three-Dimensional Spatial Domains; An Updated Version—GRID3D-V2. NASA TM-103766, 1990.

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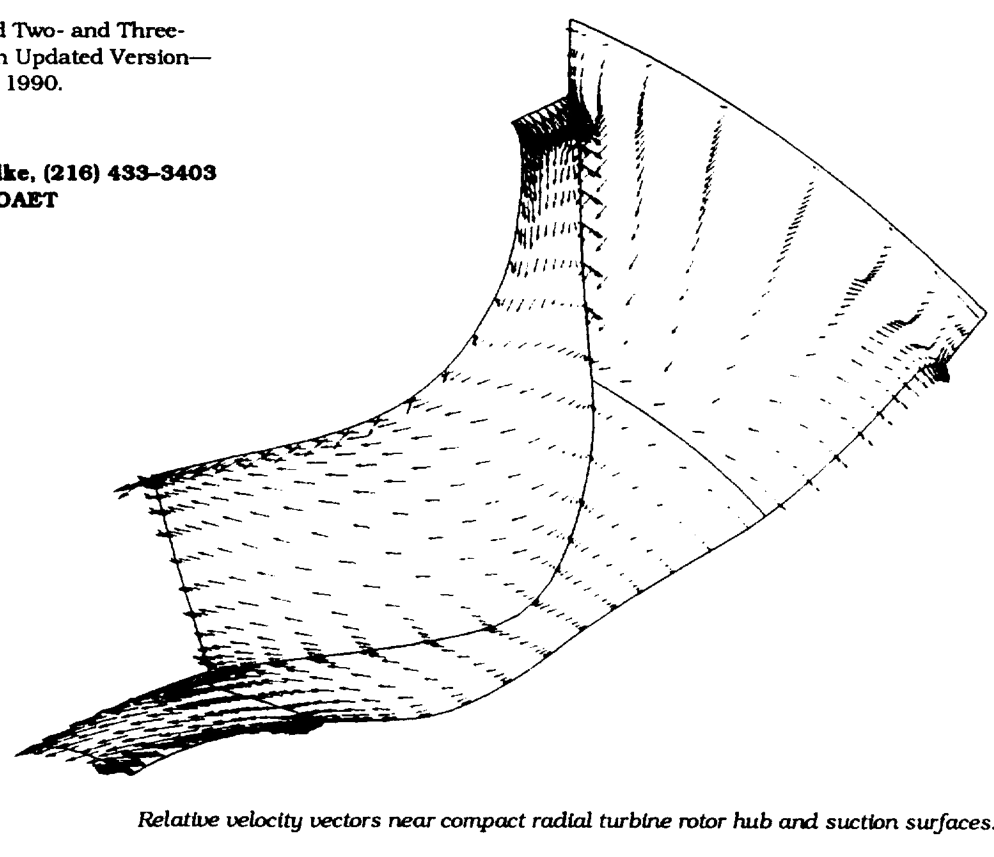
Aerodynamic Analysis Performed on Compact Radial Turbine

The use of radial turbines is advantageous in small propulsion systems because of the high efficiencies and large pressure ratios achievable in one stage. However, the size and weight of present radial turbine designs make them undesirable for future advanced aircraft applications. A compact radial turbine that is 40 to 50 percent shorter in axial length and 20 to 30 percent lighter than current state-of-the-art radial turbines has been designed and fabricated by Pratt & Whitney and tested at NASA Lewis.

In an effort to understand the complex flow physics associated with the compact radial turbine operation and to help explain experimental data, a computational study of the rotor flow field was undertaken. A steady, three-dimensional Navier-Stokes code developed at NASA Lewis was used for the analysis. Real turbine effects such as hub and tip clearance and hub surface rotation or nonrotation were modeled. Progressively



Relative velocity vectors near compact radial turbine rotor hub and suction surfaces.

improved computational models were employed, including an inviscid solution, a viscous solution without clearance, and a viscous solution with clearance. Comparisons of the calculated flow fields with test data showed good agreement with exit total pressure and total temperature but rather poorer agreement with exit flow angle. Modeling viscous effects improved correlation with experimental data; modeling hub and tip clearances further improved some comparisons.

Future work entails using the code's multiblade-row capability to analyze the compact radial turbine as a stage. In such a calculation the stator and rotor blade rows influence each other through the use of "body forces" that simulate the effects of each blade row. It is hoped that with experience, three-dimensional Navier-Stokes calculations such as this may be used not only as analysis tools, but also to improve future turbomachinery designs.

Bibliography

Heidmann, J.D.; and Beach, T.A.: An Analysis of the Viscous Flow Through a Compact Radial Turbine by the Average Passage Approach. ASME Paper 90-GT-64, June 1990. (Also NASA TM-102471.)

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NASA/Pratt & Whitney Mixer-Ejector Nozzle Tested

In response to recent interest in high-speed civil transports, NASA has begun a program to develop the enabling technology required by such an aircraft. As part of this program a cooperative nozzle test was conducted by NASA and Pratt & Whitney in the NASA Lewis 9- by 15-Foot Low Speed Wind Tunnel. The concept tested was a mixer-ejector nozzle, developed by Pratt & Whitney, consisting of a two-dimensional lobed mixer nozzle followed by a short ejector section. The objectives of the test program were to determine the amount of ejector pumping, the degree of mixing, and the noise reduction achieved.

Mixer-ejector test model.

Pumping levels on the order of 90 percent of ideal were demonstrated. Exit pressure and temperature traverse data showed that there was good mixing between the primary and secondary streams. With the mixer-ejector it was possible to both mix and diffuse the flow simultaneously. The diffusing-mixing section gave an increase in pumping at conditions for which the ejector was not choked at the inlet.

By entraining and rapidly mixing large amounts of air in a short exhaust system, the ejector suppressor nozzle can produce an exhaust that is significantly slower and quieter than the flow from the primary nozzle alone. The ejector suppressor nozzle tests demonstrated significant reduction in low-frequency noise with little reduction at high frequency. The high-frequency noise is generated within the ejector and can be absorbed by acoustic treatment.

Overall results from this program, including the demonstrated ejector pumping levels and the low-frequency noise reduction, are considered to be sufficiently encouraging to warrant continued development of the mixer-ejector as a candidate noise-reduction device for the high-speed civil transport.

Bibliography

Krejsa, E.A., et al.: Noise Measurements From an Ejector Suppressor Nozzle in the NASA Lewis 9- by 15-Foot Low Speed Wind Tunnel. AIAA Paper 90-3983, Oct. 1990. (Also NASA TM-103628.)

Lord, W.K., et al.: Mixer-Ejector Nozzle for Jet Noise Suppression. AIAA Paper 90-1909, 1990.

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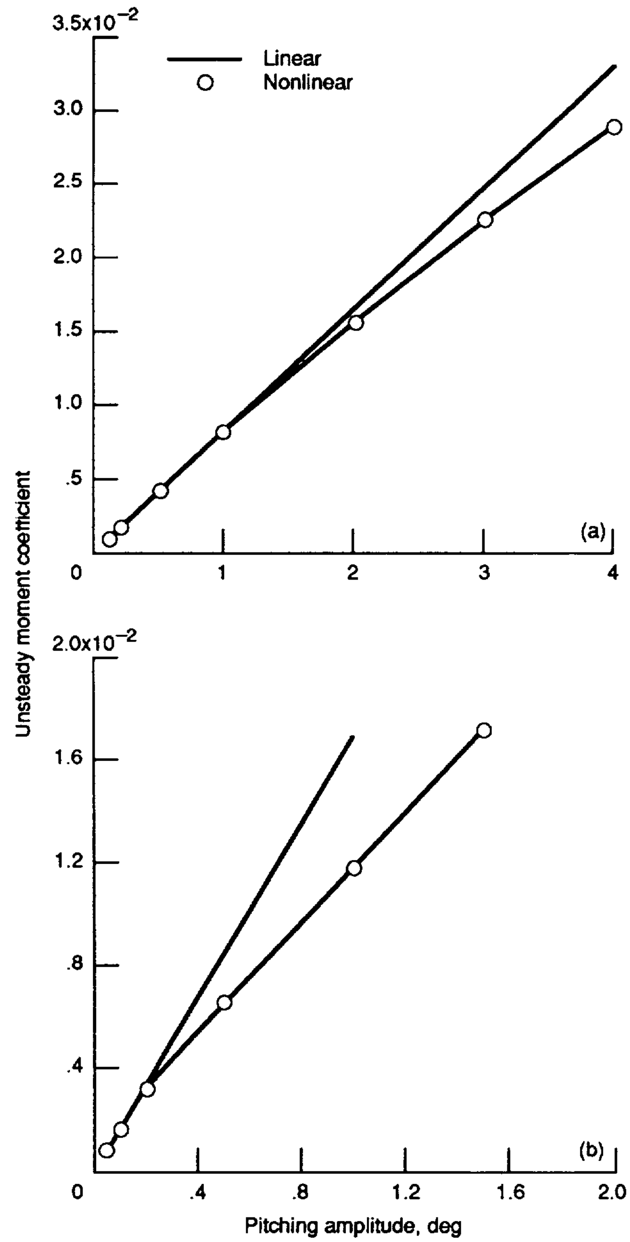
Euler Code Predicts Nonlinear Behavior of an Oscillating Cascade

The accurate prediction of flutter and fatigue in turbomachinery blades is always essential for designers in the propulsion industry. Designing against flutter and fatigue failures becomes a challenge as structural designs become less conservative. Examples include recent advanced turboprops and ducted propellers, which have increased blade sweep and have periodic forces on the blades because of their angle-of-attack operation. Many existing aerodynamic analysis models are based on linear theory and cannot predict the onset of nonlinear behavior. Therefore, NASA Lewis has developed a two-dimensional, compressible Euler code that predicts the unsteady aerodynamics associated with oscillating airfoils in a cascade.

On the basis of work with isolated airfoils, nonlinearity is expected for flows with strong shocks undergoing moderate motion. The present work investigates cascades where the nonlinear behavior is induced by varying the amplitude of oscillation. Several cascade geometries and flow conditions have been tried for cases with strong shocks on both the upper and lower surfaces of the airfoils. The magnitudes of the unsteady forces caused by pitching the airfoils were computed for various amplitudes of oscillation. The Euler predictions typically showed deviation from linearity for pitching amplitudes greater than about 1°. An exception to this trend was found for cases where the blade passages choke intermittently during the pitching cycle. Here, the nonlinearity occurred at a lower amplitude.

Further parametric studies are certainly needed to verify that these results are typical. For the flutter problem the solutions of



(a) 0° interblade phase angle (without choking).
(b) 180° interblade phase angle (with intermittent choking).

Typical predictions of unsteady moment coefficient versus pitching amplitude.

interest have small oscillation amplitudes, and all of the solutions investigated with this code for small oscillation amplitudes were found to be linear. A possible exception is when the response from the blade structure is included, and a limit to cycle behavior may require modeling higher amplitudes when the flow is nonlinear. In forced-response problems, if the effective inflow angle to the blade changes by more than 1°, there may be nonlinearities in the unsteady flow field when strong shocks are present, especially when the blade passages choke. The compressible Euler code is a useful tool for identifying the nonlinear flow field in oscillating cascades.

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Swirl Recovery Vanes Have Slight Effect on Cruise Noise of an Advanced Propeller

Advanced-turboprop-powered aircraft have the potential for significant fuel savings over equivalent-core-technology turbofan-powered aircraft. Both single- and counterrotation propellers have been investigated by NASA Lewis. Counterrotation propellers have a theoretically higher efficiency than single-rotation propellers because the second row of blades is able to recover some of the residual swirl left from the forward set of blades. In this investigation a single-rotation model propeller was tested in the NASA Lewis 8- by 6-Foot Wind Tunnel with and without a fixed set of swirl recovery vanes behind the propeller. The intent of these vanes is to recover some of the residual swirl from the propeller without the added complication of a second set of rotating blades, such as exists in the counterrotation propeller.

The noise generated by advanced propellers is of concern as a cabin environment problem for the airplane at cruise. The concern here was that the swirl recovery vanes could create additional noise by their interaction with the propeller wakes and vortices. The SR-7A model propeller was tested for acoustics with and without the downstream swirl recovery vanes to determine the effect of the vanes on the cruise noise. The swirl recovery vanes were installed in both forward and aft positions behind the blades. The experiments showed no additional interaction noise from the installation of the vanes. The swirl recovery vanes did result in some small reduction in the propeller noise as a result of the vanes unloading the propeller. The vanes showed more noise reduction when installed in the forward position than when installed in the aft position because the vanes unloaded the propeller more in the forward position. The experiments demonstrated a slight cruise noise advantage when the swirl recovery vanes were installed behind a single-rotation propeller.

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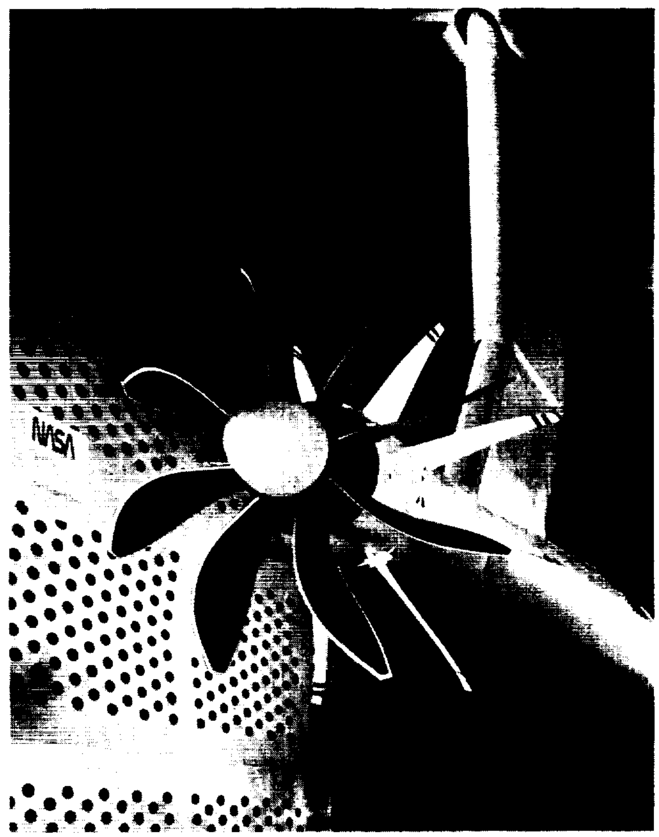
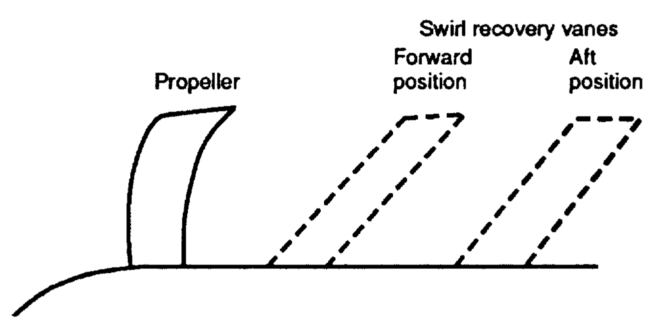


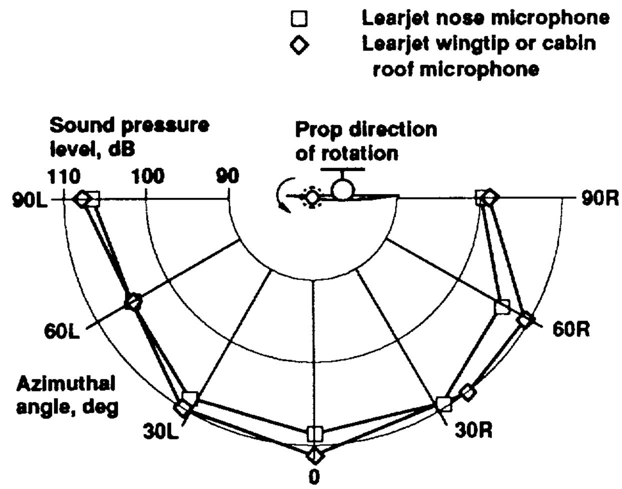


Propeller with swirl recovery vanes.

In-Flight Source Noise Tests Completed on an Advanced Full-Scale, Single-Rotation Propeller

The advanced turboprop has been shown to achieve significant fuel savings over current turbofan engines while operating at similar flight conditions (35,000-ft altitude and Mach 0.8). However, there is concern about noise levels generated by the turboprop both inside the aircraft cabin and on the ground. Flight tests to define the far-field tone source at cruise conditions have been completed on a full-scale SR-7L advanced single-rotation turboprop. This program, designated "PTA" (Propfan Test Assessment), involved extensive aeroacoustic testing of the installed propeller, which was mounted on the left wing of a Gulfstream II aircraft. Lockheed-Georgia was the prime contractor for the modified Gulfstream aircraft, and the 9-ft-diameter, eight-blade advanced propeller was designed and built by the Hamilton Standard Division of United Technologies.

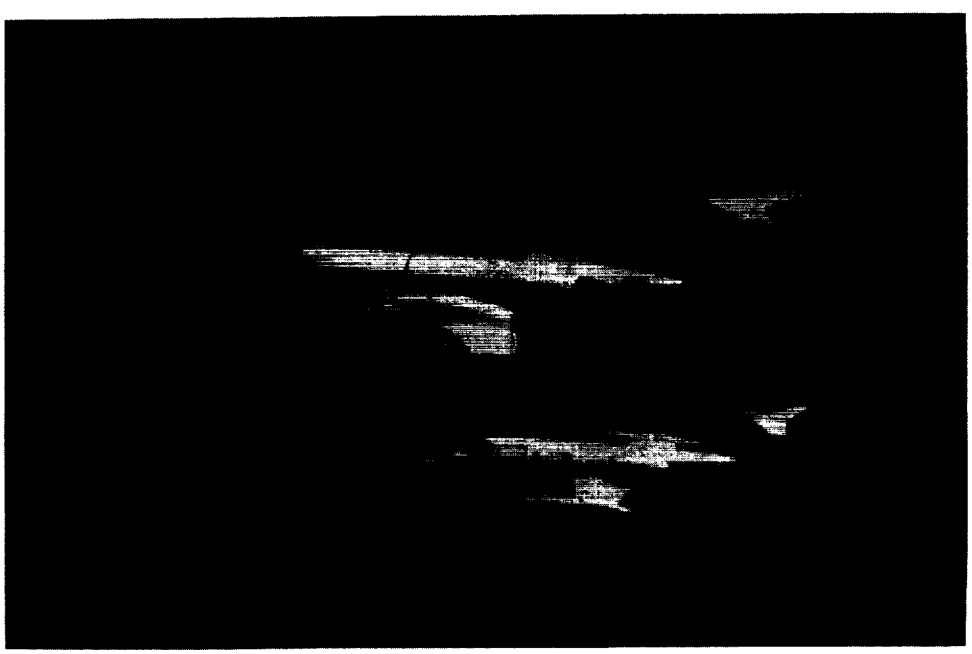
A primary objective of the PTA test was to map the source noise directivity pattern of the SR-7L propeller under actual flight conditions. Data flights included both ground noise measurements and in-flight source noise mapping by the acoustically instrumented NASA Lewis



Typical SR-7L BPF tone azimuthal directivity.

Learjet. Acoustic data were also taken on the PTA aircraft at fuselage locations and on an outboard microphone boom.

The PTA flight tests provided full-scale acoustic results for several propeller operating conditions. En route noise data were acquired near the propeller source with the Learjet and were also measured on the ground. Concurrent atmospheric condition measurements were taken to better define acoustic propagation conditions. These data will be used by



NASA Learjet flying in formation with PTA aircraft.

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engineers at NASA Langley for propeller noise code validation.

Bibliography

Woodward, R.P.; and Loeffler, I.J.: In-Flight Source Noise of an Advanced Full-Scale Single-Rotation Propeller. AIAA Paper 91-0594, Jan. 1991. (Also NASA TM-103687.)

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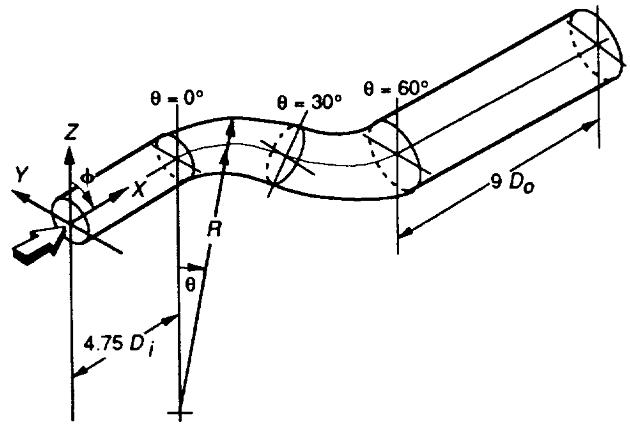

Schematic of diffusing S-duct.

Navier-Stokes Analysis Predicts Flow in Three-Dimensional S-Ducts

Many aircraft employ curved rectangular and circular duct geometries in the inlet and exhaust of their propulsion systems. The performance of these types of duct, which may have strong secondary flows, is usually determined by wind tunnel testing. Recently, computational fluid dynamics capabilities have improved, and full Navier-Stokes computer programs are used to predict the flows in these ducts.

Vortex pairs are evident in the exit planes of S-ducts, transition ducts, and curved rectangular ducts. These vortices are due to secondary flows induced by pressure gradients. The mechanism that produces the low total pressure region at the exit is an inviscid rotational phenomenon, provided that an inlet boundary layer is present.

The flow fields were modeled for a diffusing S-duct with a circular cross section and two 30° bends. The average inlet Mach number was 0.6 and the duct area ratio was 1.5. Experimental oil flow patterns and predicted wall boundary layer streamlines taken near the boundary layer flow separation point were in good qualitative agreement. The computed total pressures were also generally in good agreement with the experimental data, and the velocity vectors were in qualitative agreement with the data. Similar results were obtained when using two different Navier-Stokes computer programs, different turbulence models, and different grids.

This capability is used to compute the flow fields and performance of three-dimensional aircraft inlets and nozzles.

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Aerospace Technology

Materials

Advanced High-Temperature Engine Materials Technology Makes Progress

The objective of the Advanced High-Temperature Engine Materials Technology (HITEMP) Program is to generate technology for revolutionary advances in composite materials and their structural analysis that will enable the development of 21st century civil propulsion systems with greatly increased fuel economy, improved reliability, extended life, and reduced operating costs. The primary focus is on polymer, metallic, intermetallic, and ceramic matrix composites. These composite materials are being developed for eventual use in fans, compressors, turbines, combustors, and exhaust nozzles for future civil transport aircraft.

NASA considers this program to be a focused materials and structures research effort that builds upon our basic research programs and will feed results into application-oriented projects such as the proposed NASA new initiative to develop the technology for a 21st century high-speed civil transport. HITEMP is also closely coordinated with the Department of Defense/NASA Integrated High Performance Turbine Engine Technology (IHPTET) Program, and new composite materials from HITEMP may be used in future military applications.

Intensive collaboration between NASA Lewis structures and materials researchers has resulted in defining fiber coatings to accommodate the inherent mismatch in coefficients of thermal expansion between reinforcing fibers and the matrices of intermetallic matrix composites. Lewis researchers have developed a new chemical addition to polymers that increases their molecular weight, thus raising the potential use temperature of polymer matrix composites while still maintaining good processability. A new technique, a bend test conducted at temperatures from 2400 to 3000 °F, has been developed to measure the creep resistance of ceramic fibers. Single-crystal silicon carbide whiskers have been shown to be the most creep-resistant fiber yet tested. This tech-nique is now being used by researchers at several industrial and Government laboratories. New mechanical test capability to evaluate ceramic matrix composites at temperatures up to 3000 °F is now operational.

A cooperative effort with an engine company and Lewis structures and materials researchers has resulted in substantial progress in the design, development, characterization and life prediction of a continuous-fiber-reinforced titanium alloy engine component. This very successful cooperative project will serve as a model for additional future efforts within HITEMP.

The third annual review of the HITEMP program was held Oct. 30 and 31, 1990. Details of research accomplishments are published in a conference report, NASA CP-10051.

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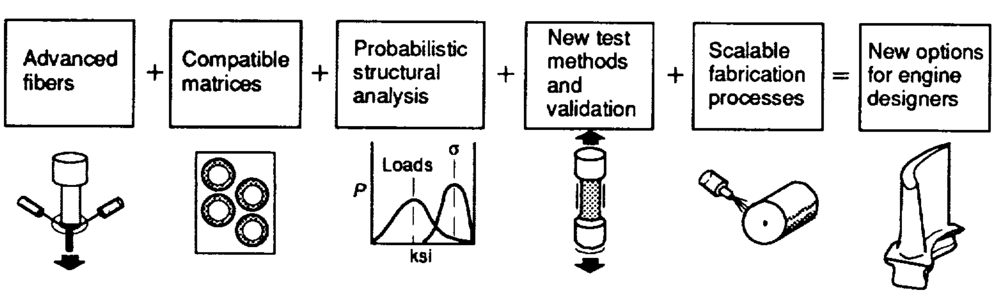


Elements of HITEMP program.

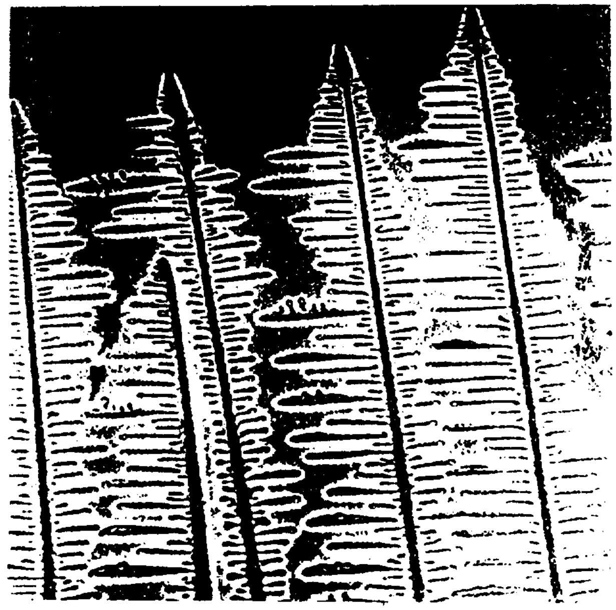
Fundamental Model Developed for Solid/ Melt Interface Morphologies

One of the more interesting and yet unsolved problems in the physical world is the formation of patterns in nature. During phase transformation, such as solidification from a melt, an intricate set of tree-like patterns known as dendrites forms. Because solidification processes are used to produce virtually all metallic components and because pattern formation occurs in so many other natural processes, theories describing the phenomena are hotly debated.

The Computational Materials Laboratory at NASA Lewis has developed a fundamental model for the early stages of solidification that does not involve mathematical or physical simplifications in its formulation. For the first time, with this novel computational technique, essential features of patterns seen in experiments can be duplicated both qualitatively and quantitatively. It has been shown that the previous inability to model the formation of patterns during solidification could be traced to assumptions made to simplify previous work.

Initial results exhibit a remarkably rich set of phenomena that parallel those seen in nature, such as surface waves originating from crystallographic defects (line and point dislocations), an early development of steady growth conditions (dendrite tip radius of curvature and growth velocity), and the emergence of large-scale patterns whose global features are independent of initial conditions.

The findings of this study are of importance for several efforts undertaken presently by NASA. From a fundamental viewpoint the problem of single-dendrite operating conditions will be explored in an upcoming space experiment, the Isothermal Dendritic Growth Experiment, now being built by the Lewis Space Experiments Division for an experiment designed by Professor M. Glicksman of Renssalaer Polytechnic Institute. From a practical viewpoint the patterns formed during solidification determine material microstructure and influence the resulting properties.



Experimental appearance of a dendritic morphology exhibited by solidifying metals, organic crystals, salts, snowflakes, etc.

This study represents an ongoing effort at NASA Lewis. Anticipated work will focus on the advanced stages of dendritic morphology development and use an improved version of the numerical model. These advances are greatly aided by the availability of supercomputers at the laboratory.

Bibliography

Pines, V.; Zlatkowski, M.; and Chait, A.: Time Development of a Perturbed Spherical Nucleus in a Pure Supercooled Liquid. I. Power Law Growth of Morphological Instabilities. Phys. Rev. A, vol. 42, no. 10, Nov. 15, 1990, pp. 6129–6136.

Pines, V.; Zlatkowski, M.; and Chait, A.: Time Development of a Perturbed Spherical Nucleus in a Pure Supercooled Liquid. II. Nonlinear Development. Phys. Rev. A, vol. 42, no. 10, Nov. 15, 1990, pp. 6137–6150.

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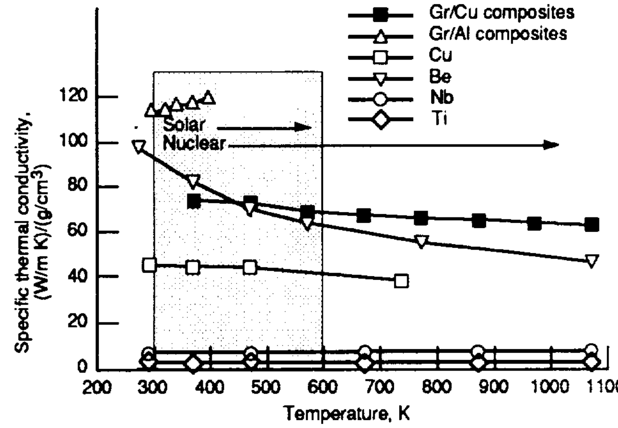
Graphite Fiber/Copper Matrix Composites Improve Space Power Radiator Fins

One of the major requirements for producing power in space is that heat be rejected by radiation to the space environment. For many power systems the waste heat radiator is the largest-area and highest-mass component. Waste heat radiators usually consist of a combination of heat pipes, fins, and pumped loops. The design and the optimum operating temperature of the waste heat radiator are dependent upon the mission, the type of power conversion device, and the heat source. Two of the key material-property-related design criteria in minimizing the mass of space power radiators are the thermal conductivity and density of radiator fin materials.



Specific thermal conductivity of candidate materials for solar and nuclear source space power radiator fins.

The high thermal conductivity, high elastic modulus, and low density of graphite fiber/copper matrix composites (Gr/Cu) offer the potential of producing lightweight radiator fin materials for space power systems. Gr/Cu composites reinforced with ultra-high-modulus graphite fibers have thermal conductivities similar to that of copper, densities in the range of titanium, and moduli comparable to that of beryllium.

Radiators for space power systems with solar heat sources have operating temperatures of 300 to 600 K; those for power systems with nuclear heat sources have operating temperatures up to 1000 K. Comparing specific thermal conductivity (thermal conductivity divided by density) as a function of temperature for several candidate radiator fin materials shows that Gr/Cu composites have better specific thermal conductivity than beryllium at higher temperatures and are much better than unreinforced copper, titanium, and niobium alloys at all temperatures. This high specific thermal conductivity allows an optimized radiator design with Gr/Cu radiator fins that can reduce the minimum total radiator mass by almost 6 percent at 1000 K.

The properties of Gr/Cu composites are very anisotropic. Thermal conductivity in the longitudinal direction (parallel to the fiber) is about the same as that of copper; conductivity in the transverse direction (perpendicular to the fiber) is significantly lower. Thermal expansion of Gr/Cu is nearly zero in the longitudinal direction and is greater than copper in the transverse direction. These anisotropic properties offer the designer the ability to tailor the properties of the composites by optimizing the fiber content, the fiber type, and the fiber angleply orientation to give the composites the proper design tradeoff of thermal conductivity, modulus, density, and thermal expansion properties required for a given application.

Research is ongoing at NASA Lewis to determine the properties of unidirectionally reinforced Gr/Cu composites. The effect of fiber content on thermal conductivity, elastic modulus, and thermal expansion is being identified in both the longitudinal and transverse directions. Similar property determinations are being conducted for angleplied composites. Process development is under way to make composite fabrication more economical and to enhance fiber/matrix bonding to improve transverse strength and high-temperature stability.

In addition to application to space power radiator fins, Gr/Cu composites also offer the potential of use as actively cooled high-heat-flux structures for hypersonic aircraft. These applications require higher strength and higher operating temperatures than space power radiator fin applications. Work is ongoing to apply the Gr/Cu fabrication technology developed for radiator fins to high-heat-flux hypersonic structures.

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Fabrication Processes Developed for Intermetallic Matrix Composites

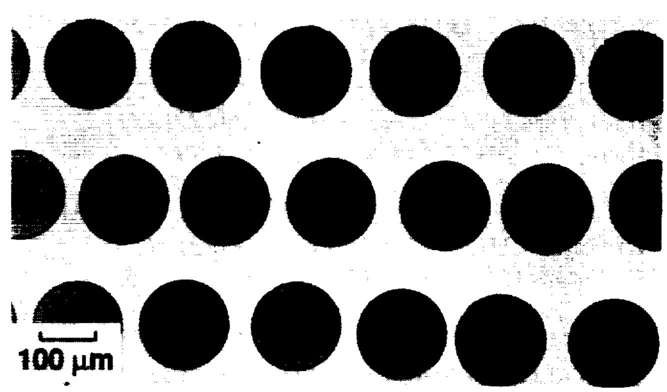
Development of processes for fabricating intermetallic matrix composite (IMC) materials is an ongoing program at NASA Lewis. Composite materials are needed for various applications that require combinations of properties not available with conventional materials. Research and development are currently being done on these materials under the HITEMP Program. These processes impact the High Speed Civil Transport (HSCT), National Aerospace Plane (NASP), and Space Power programs as well.

Two primary processes are being developed in house for producing IMC's. One is a powder metallurgy approach called the powder cloth process; the other in a thermal deposition technique known as the arc spray process. Final consolidation of composite materials is accomplished in a highly instrumented vacuum hot pressing (VHP) operation or by hot isostatic pressing (HIP), which utilizes extremely high gas pressure to bond the components at elevated temperatures. The goal of current efforts involves determining critical process variables and their relationships to the composition, microstructure, and properties of the materials produced.

The powder cloth process is a more mature process than arc spraying and is the primary technique for producing IMC test specimens at NASA Lewis. The matrix phase is processed into a flexible, cloth-like sheet by combining the matrix powder with a fugitive organic binder to produce a pliable "dough" that is rolled into sheets of powder cloth. The reinforcing fiber mat is prepared by wrapping a continuous length of reinforcing fiber around a lathe-mounted drum. The fibers are then glued together with an organic binder. The composite panel is assembled by stacking alternating layers of matrix cloth and fiber mat in a combination that achieves the desired panel thickness and fiber orientation. Finally, the binders are removed and the powder cloth/fiber mat stack is consolidated during VHP. This process is supporting development efforts in titanium-, nickel-, iron-, and niobium-aluminide IMC's.

The arc spray process, originally developed and patented at NASA Lewis for fabricating composites, is a thermal deposition process that utilizes the matrix material in the form of wire. The matrix wire feedstock is melted in a dc electric arc, atomized by an inert gas jet, and propelled toward a target as a stream of molten droplets. The target is a drum on which the reinforcing fibers for the composite have been wound. The drum revolves and translates during spraying to ensure uniform deposition of the matrix onto the fibers. The completed monotape is cut into panels and stacked as an assembly for consolidation into a fully dense, multi-ply composite.

Potential advantages of the arc spray process are being evaluated. Since the matrix feedstock is a wire, there is the potential for achieving lower oxygen levels than in processes using powder because of the wire's much lower specific surface area. Directly binding fiber into position with the matrix material rather than using a fugitive binder also creates further potential for chemistry



Uniform fiber distribution achieved in SiC/titanium-aluminide composite fabricated by wire arc spray method.

improvements by reducing the possibility of contamination from binder decomposition products. Since there is no need to accommodate removal of a binder, flexibility in processing options for consolidation is enhanced. Finally, holding the fibers in position with the matrix material rather than with a fugitive binder results in a more uniform distribution of fibers in the final composite. Titanium-, nickel-, and iron-aluminide IMC's have been produced by this method. A patent application concerning fabrication of IMC's by several arc spray approaches has been filed.

Bibliography

Pickens, J.W., et al.: Fabrication of Intermetallic Matrix Composites by the Powder Cloth Process. 13th Conference on Metal Matrix, Carbon, and Ceramic Matrix Composites, J.D. Buckley, ed., NASA CP-3054-Pt-2, 1989, pp. 515-532.

Pickens, J.W.; and Watson, G.K.: SiC/Ti_3AlNb Composite Fabrication by the Arc Spray Process. 14th Conference on Metal Matrix, Carbon, and Ceramic Matrix Composites, J.D. Buckley, ed., NASA CP-3097, 1990, pp. 711-732.

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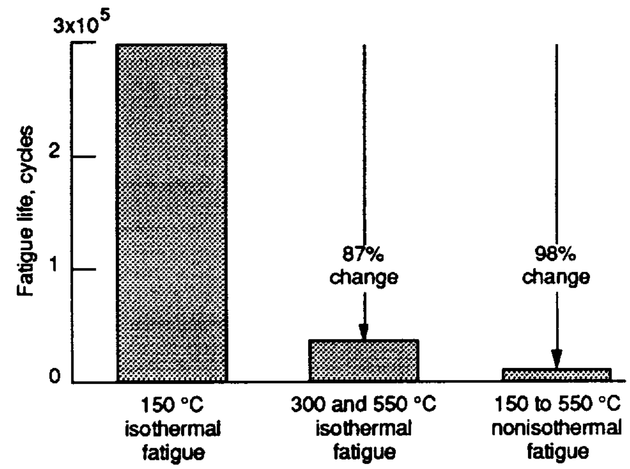
Fatigue Behavior of an SiC/Titanium Composite Studied

Titanium matrix composites are currently being considered as lightweight replacements for superalloys in a variety of aerospace applications. One such application would utilize beta titanium alloys reinforced with silicon carbide (SiC) fibers as the material of choice for disks of advanced compressor designs. Using these composites in compressors of future turbine engines is one means of achieving the performance goals of the NASA HITEMP and Department of Defense/NASA IHPTET programs. As high-temperature fatigue is a life-limiting factor in disk design, NASA Lewis has undertaken a fundamental study to assess the fatigue behavior of a beta titanium alloy, Ti-15-3, reinforced with SiC fibers.



Fatigue life of SiC/Ti-15-3 composite at 0.44 percent strain range for various test conditions.

In the first phase of this study the isothermal fatigue behavior of unidirectionally reinforced SiC/Ti-15-3 composite was investigated at 150, 300, and 550 °C. The results of these tests have shown that isothermal fatigue life decreases dramatically above 150 °C. In the second phase of this study the nonisothermal fatigue behavior of the composite was assessed at 150 to 550 °C. In the nonisothermal fatigue test the mechanical load and temperature were both varied in a systematic fashion, and therefore additional damage mechanisms associated with the thermal expansion mismatch between the SiC fiber and the titanium matrix could be activated. Nonisothermal fatigue testing was found to reduce fatigue life beyond that observed in isothermal tests. In addition, the nonisothermal life degradation was much more severe as the maximum temperature increased, for a given temperature range. These data suggest that oxidation resistance of the beta titanium matrix is an important factor controlling fatigue life under isothermal and nonisothermal conditions.

Future work on this composite system will focus on identifying the mechanisms by which the air environment degrades fatigue life, especially under nonisothermal conditions. This will be accomplished by running isothermal and nonisothermal fatigue tests in vacuum and carefully comparing the failure sequence with comparable tests run in air.

Bibliography

Gabb, T.P.; Gayda, J.; and MacKay, R.A.: Nonisothermal Fatigue Degradation of a SiC/Ti Composite. HITEMP Review 1990, NASA CP-10051, 1990, pp. 32-1 to 32-12.

Gayda, J.; Gabb, T.P.; and Freed, A.D.: The Isothermal Fatigue Behavior of a Unidirectional SiC/Ti Composite and the Ti Alloy Matrix. NASA TM-101984, 1989.

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Simple Creep Test Developed for Ceramic Fibers

Improvement in the creep resistance of ceramic fibers is essential for the advancement of fiber-reinforced ceramic matrix composites (CMC's). However, tensile tests for evaluating creep are extremely difficult to apply to small-diameter fibers. A simple bend test has been developed that measures the creep-related stress relaxation of ceramic fibers. The bend stress relaxation test has been used not only to rank the creep resistance of various fibers but also to accurately predict creep under tensile conditions.

The bend stress relaxation experiment is typically performed by tying a fiber into a loop or constraining it with a mandrel of known radius of curvature R_o. The fiber is then subjected to heat treatment of a specific time, temperature, and environment. After treatment the fiber loop is broken or the constraint is removed, and if the fiber has relaxed (crept), it retains a residual bend characterized by a radius of curvature R_a. The stress relaxation ratio m is measured from R_o and R_a and is a measure of the ratio of elastic stress remaining in the fiber loop after the heat treatment to the initial elastic stress applied by R_o. This ratio is related to the creep of the fiber and can be used to compare fibers tested at identical conditions.

Several commercial and developmental fibers have been tested over a wide range of times and temperatures and ranked for creep resistance. Significant differences were observed, allowing insight to be gained into the creep mechanisms. This insight, which can be used to predict use lifetimes for specific fibers, is being combined with fracture strength and environmental durability results to determine optimum fiber microstructure and to guide new fiber development for ceramic matrix composites.

Bibliography

Morscher, G.N.; and DiCarlo, J.A.: A Simple Test for Thermomechanical Evaluation of Ceramic Fibers. Submitted to J. Am. Ceram. Soc. Comm., 1990.

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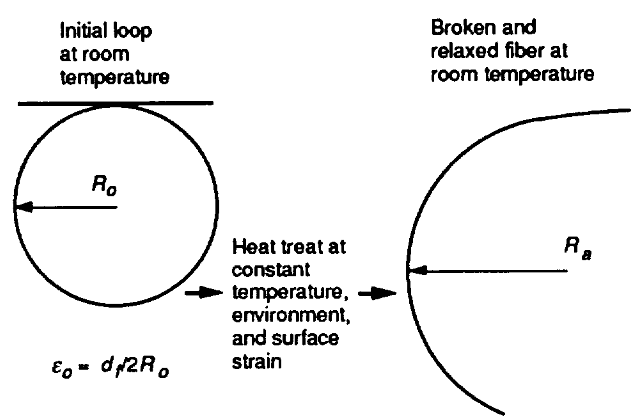


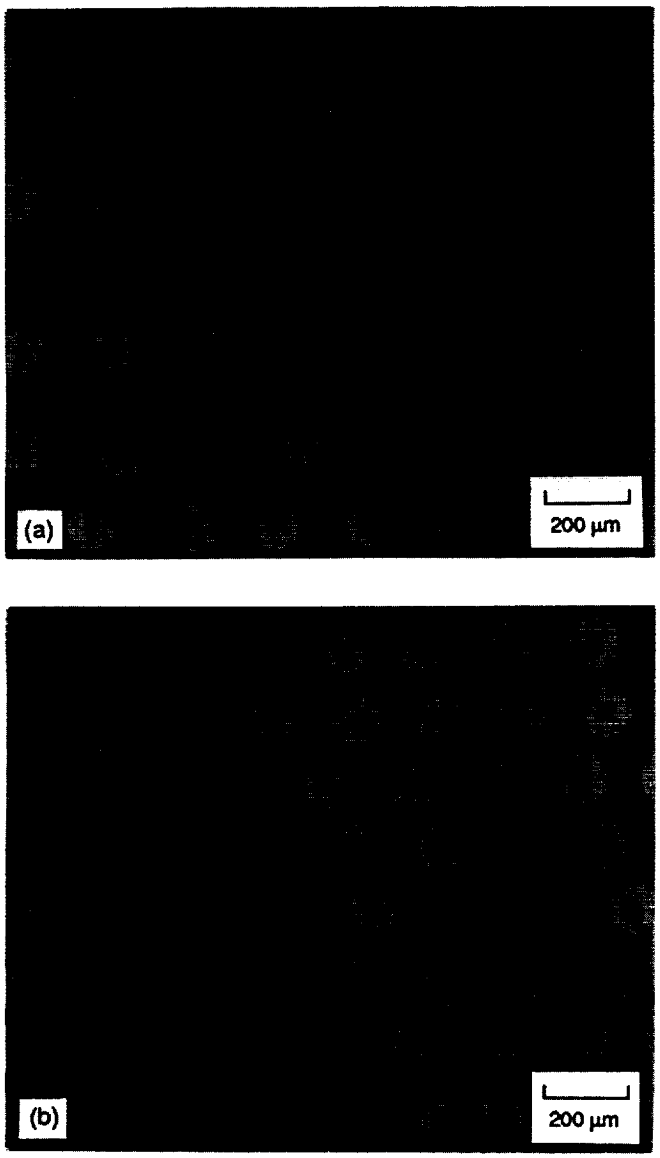
Stress relaxation ratio, $m = \sigma(t)/\sigma(0) = 1 - R_o/R_a$

where R_a depends on treatment time, temperature, environment, and initial surface strain.

Fiber bend stress relaxation test.

Hot Isostatic Pressing Improves Performance of SiC-Fiber-Reinforced, Reaction-Bonded SiN Matrix Composites

Ceramic composites are critical for the development of engine components for advanced civil transports. These composites must be lightweight and have high strength and modulus, high thermal conductivity, and environmental stability. Hot isostatic pressing (HIPing), which involves material consolidation under gas pressure (up to 310 MPa) at high temperatures (up to 2200 °C), has been used to eliminate matrix porosity in silicon-carbide-fiber-reinforced, reaction-bonded silicon nitride (SiC/RBSN) composites. These HIPed composites contained a small amount of an oxide sintering additive, magnesium oxide, which made it possible to greatly reduce the temperature needed to achieve complete matrix densification. Elimination of matrix porosity should minimize oxidation problems previously observed in SiC/RBSN composites while also improving some mechanical properties and maximizing the thermal conductivity.



(a) As nitrided (density, 2.5 g/cm^3).
(b) HIPed (density, 3.1 g/cm^3).

Optical micrographs of polished cross sections of SiC/RBSN composites containing a small amount of magnesium oxide.

In a preliminary study HIPing led to improvements in the elastic modulus and the first matrix cracking strength of 50 and 15 percent, respectively (ref. 1). However, strength degradation of the fibers during HIPing reduced both the strain capability beyond matrix fracture and the ultimate tensile strength. A more extensive examination of the effects of the HIPing variables (pressure, temperature, and hold time) on the densification and microstructure of SiC/RBSN composites containing magnesium oxide led to the identification of processing conditions that should minimize fiber degradation and thus improve composite performance (ref. 2).

The development and mechanical property testing of SiC/RBSN (with magnesium oxide) composites HIPed at lower temperatures and the HIPing of composites containing various other oxide additives, various types of SiC fibers, or both are efforts currently in progress.

References

1. Bhatt, R.T.; and Kiser, J.D.: Matrix Density Effects on the Mechanical Properties of SiC/RBSN Composites. NASA TM-103098, 1990.

2. Kiser, J.D.; and Bhatt, R.T.: Effect of Hot Isostatic Pressing (HIPing) on the Microstructure of SiC Fiber-Reinforced RBSN Matrix Composites Containing an Oxide Additive. NASA CP-10051, 1990, pp. 52-1 to 52-13.

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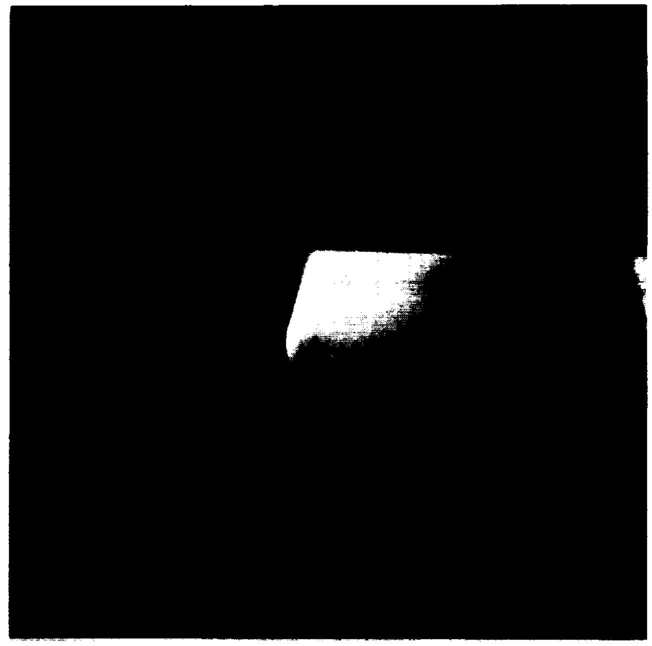
Ceramic Composite Turbopump Blade Survives Severe Thermal Shock

The most advanced liquid-propellant rocket engine available today is the space shuttle main engine (SSME). Thermal shock is a critical parameter in the SSME turbopump. (The current metallic turbine blades fail because of thermal fatigue.) A unique NASA Lewis hydrogen/oxygen rocket engine test rig that simulates the SSME turbopump start transient was used to test turbine blades made of fiber-reinforced ceramic matrix composites (FRCMC's). A number were found to be unaffected by multiple thermal shocks of up to 1400 °C per second.

Contracts with Rocketdyne and General Electric provided NASA Lewis with FRCMC turbine airfoil shapes. The C/SiC airfoil provided by Rocketdyne (manufactured by Société Européenne de Propulsion) survived fifty 1-second thermal shock cycles from ambient to 1800 °C (3300 °F). Visual examination of the blade indicated that only a small amount of leading-edge erosion occurred. This erosion did not start until after 20 shock cycles had been completed. These results are highly significant and demonstrate the viability of applying FRCMC's for use in the turbopump of an advanced rocket engine. A contract to fabricate and test a full-scale turbopump component in a rocket engine environment is in place at Rocketdyne.



FRCMC turbine blade during rocket engine rig test.

Bibliography

Eckel, A.J.; and Herbell, T.P.: Thermal Shock of Fiber Reinforced Ceramic Matrix Composites. 13th Conference on Metal Matrix, Carbon, and Ceramic Matrix Composites, NASA CP-3054-Pt-1, J.D. Buckley, ed., 1989, pp. 153-162.

Herbell, T.P.; and Eckel, A.J.: Ceramic Composites for Rocket Engine Turbines. NASA TM-103743, 1991.

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Fiber-Reinforced Celsian Glass-Ceramic Matrix Composites Tested at Room Temperature

Strong, tough, and environmentally stable structural materials are needed for high-temperature applications in advanced high-efficiency, high-performance engines for aerospace propulsion and power systems. A continuous-fiber-reinforced celsian, $BaO.Al_2O_3.2SiO_2$ (BAS), glass-ceramic matrix composite (FRCMC) is one such material. Celsian is highly refractory, is oxidation resistant, and has low thermal expansion (2.3×10^{-6}/°C).

On heat treatment of the BAS glass the metastable hexacelsian phase crystallizes out. This phase has high thermal expansion (8.0×10^{-6}/°C) and undergoes structural change at 300 °C accompanied by a large volume change. Also, the kinetics of hexacelsian-to-celsian phase transformation is very sluggish. Fortunately, NASA Lewis has recently been successful in identifying certain additives in the presence of which the celsian phase crystallizes out directly in the BAS glass.

At present, FRCMC's are being fabricated in house by using various commercially available continuous ceramic fibers under different processing conditions and are being tested at room temperature. Nearly fully dense (95 to 98 percent) chemical-vapor-deposited (CVD), SiC-monofilament-reinforced glass-ceramic composites have been obtained with first matrix crack stress above 200 MPa and ultimate flexural strength above 500 MPa under ambient test conditions. Once the processing parameters have been optimized in the near future, the thermochemical and thermomechanical behaviors of these FRCMC's will be tested under the hostile environments to be encountered in advanced rocket engines.

Bibliography

Bansal, N.P.; and Setlock, J.A.: Silicon Carbide Fiber-Reinforced Celsian Glass-Ceramic Matrix Composites. NASA CP-10051, 1990, pp. 59-1 to 59-15.

Bansal, N.P.; Setlock, J.A.; and Drummond, C.H.: Celsian Glass-Ceramic Composites. NASA CP-10039, 1989, pp. 62-1 to 62-12.

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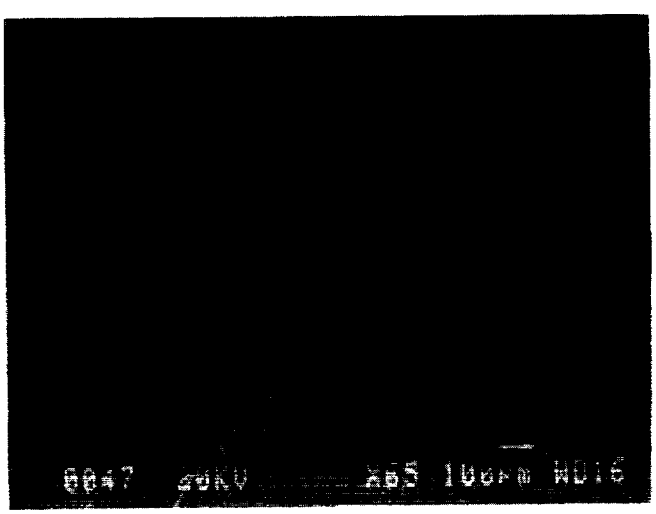
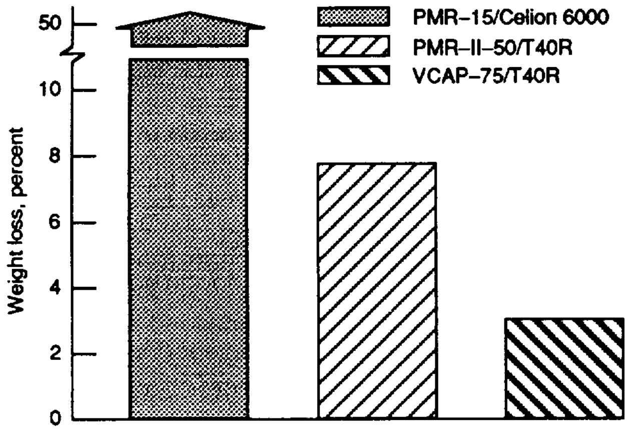


Microstructure of CVD, SiC-fiber-reinforced celsian glass-ceramic matrix composite showing uniform fiber distribution.

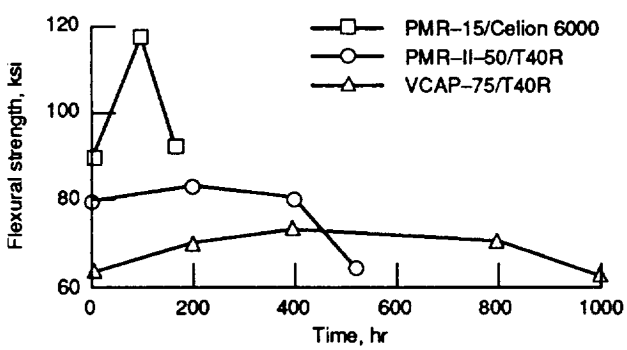
VCAP Matrix Resins Improve 700 °F Composite Performance

In order to keep up with the increasing material demands of advanced aeropropulsion systems, NASA Lewis has been involved in an ongoing, long-term program to develop high-temperature-resistant matrix resins for aircraft engine applications. Early studies at NASA Lewis led to the development of the PMR-15 polyimides. Further work led to the improved second generation, PMR-II polyimides, which have better thermo-oxidative stability than PMR-15. Both the PMR-15 and PMR-II polyimide resins offer excellent processability and thermo-oxidative stability (TOS) at use temperatures as high as 600 °F. Recently introduced high-molecular-weight (HMW) formulations of the PMR-II resins provide improved TOS at use temperatures as high as 700 °F (ref. 1). The HMW PMR-II resins are autoclavable and exhibited good retention of 700 °F mechanical properties during continuous 700 °F air exposure for 500 hr or more. Current program efforts are aimed at extending the useful life and upper use temperature by using more thermally stable reactive prepolymer endcaps, which control prepolymer molecular weight prior to the final addition reaction cure of the resin.

One reactive endcap that offers significant potential for improving the TOS of addition-cured polyimides is para-aminostyrene (PAS). A PMR type of polyimide formulated with PAS (ref. 2) and labeled VCAP (vinyl-capped addition polyimide) uses a cure reaction sequence similar to that of PMR polymers and can be processed by the same procedures required for HMW PMR-II resins. Graphite-fiber-reinforced composites made with VCAP-75 polyimide resin provide significantly better composite weight and flexural strength retention during 700 °F air exposure than composites prepared with the PMR-15 and PMR-II-50 resins. After 500 hr of exposure to 700 °F the VCAP laminate exhibited only 2.9 percent oxidative weight loss, compared with 7.8 percent for the PMR-II-50 resin laminate. The VCAP laminate also retained 100 percent of initial 700 °F flexural strength after 1000 hr of exposure to 700 °F air, compared with approximately 75 percent



Composite weight loss after 500 hr of exposure to 700 °F air.



700 °F flexural strength retention of composites aged at 700 °F.

retention for the PMR-II-50 laminate after only 500 hr of exposure.

References

1. Vannucci, R.D.; and Cifani, D.: 700 °F Properties of Autoclave Cured PMR-II Composites. Materials-Processes: The Intercept Point, C. Prosen and D. Meth, eds., SAMPE, 1988, pp. 562-575.

2. Vannucci, R.D., et al.: Autoclavable Addition Polyimides for 371 °F Composite Applications. Proc. of the 22nd Int. SAMPE Tech. Conf., Nov. 1990. (NASA TM-103233.)

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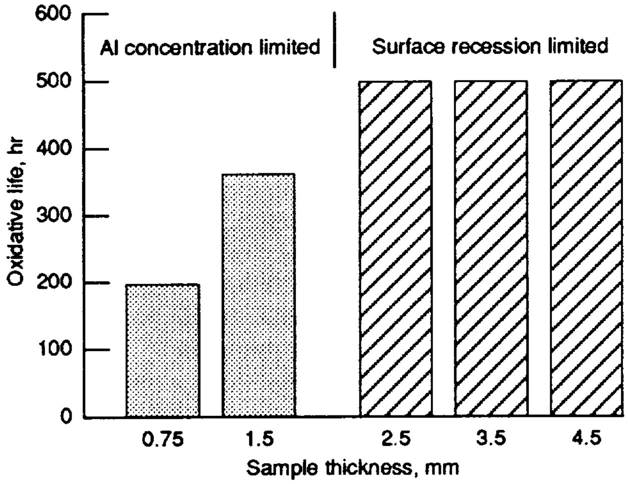
Model Predicts Oxidative Life of β NiAl

Nickel aluminides (NiAl) show significant potential for use as a matrix material in the hot section of future supersonic aircraft. One of the strengths of β NiAl is its excellent oxidation resistance when alloyed with small amounts of reactive elements, such as zirconium. The selective oxidation of aluminum to form an Al_2O_3 scale on β NiAl alloys is the basis for the oxidation resistance of these alloys. However, when aluminum is selectively oxidized, two processes occur simultaneously. The Al content of the component decreases and the surface of the component recedes owing to the loss of Al. In addition, when the component is thermally cycled, resulting in partial loss of the oxide scale, the depletion of Al and the recession of the surface are accelerated. A diffusion model has been developed at NASA Lewis to predict the oxidative lifetime of β NiAl alloys. This model uses both a critical Al concentration and a critical amount of surface recession as the life-limiting criteria. The model shows that for thin samples Al is depleted more rapidly and component life is limited by insufficient Al but that thick samples, which have a greater reservoir of Al, when oxidized under the same conditions, are more likely to be life limited by excessive surface recession.

The diffusion model, capable of being run on a desktop personal computer, is based on finite-difference techniques and simulates one-dimensional transport of Al. Input to the model consists of the initial Al composition, the concentration dependence of the interdiffusion coefficients for the test temperature, the sample thick-ness, and the rate of Al consumption, which is supplied by an oxide spalling model coupled to the diffusion model. The temperature dependence of the oxide growth and spalling process and the consequent effect on the rate of Al consumption are accounted for in the oxide spalling model. The model predicts Ni and Al concentration profiles as well as surface recession after various oxidation exposures. The model accounts for sample thickness by permitting the diffusion fields within a sample to overlap, thus accelerating the decrease in the Al concentration of a sample. Previous experimental work has shown that nonprotective oxide scales are formed on NiAl at a critical



Cyclic oxidation of β NiAl at 1400 °C (1-hr cycles).

concentration of approximately 37 to 38 at. % Al. Hence, the model can predict the oxidative lifetime due to Al depletion when the Al concentration decreases to this critical value. Similarly, a component designer may define a critical surface recession, such as 150 μm (0.006 in.). Since the model predicts surface recession after various oxidation periods, the lifetime based on a critical surface recession can also be identified.

Measured Al concentration profiles for various β NiAl alloys and after various oxidation exposures showed good agreement with the diffusion model predictions. However, further verification tests are being performed on samples of different thicknesses. The model is also being modified to account for two-dimensional diffusion and thus more accurately take into account sample edges and corners.

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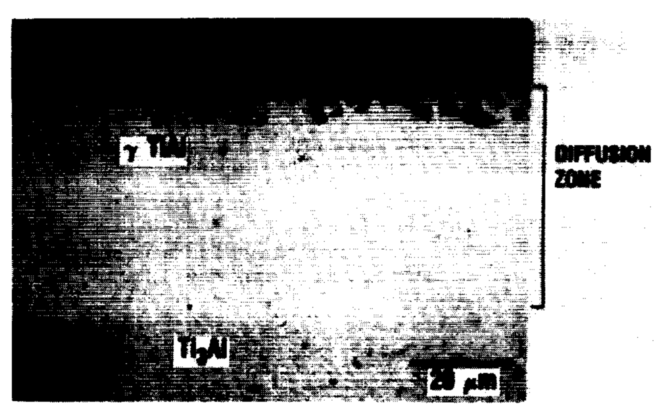
Chemical Compatibility of Alumina With Titanium Aluminides Studied

Continuous-fiber-reinforced intermetallic matrix composites based on titanium aluminide matrices are currently being considered for high-temperature engine applications because of their high strength-to-density ratio. One primary criterion for selecting a suitable fiber for a given matrix is the matching coefficient of thermal expansion (CTE) between the fiber and the matrix. Because the CTE of Al_2O_3 is reasonably matched to that of the titanium aluminides, fiber of this material would be a good candidate to reinforce titanium-aluminide-based matrices. However, the question of chemical compatibility of Al_2O_3 with titanium aluminides had to be addressed.

The chemical compatibility of Al_2O_3 with titanium aluminides was studied by exposing TiAl alloy/single-crystal Al_2O_3 (Saphikon) reaction couples to diffusion anneals at temperatures in the range 800 to 1100 °C and then characterizing the reaction products.

Significant reaction occurred between Al_2O_3 and TiAl alloys with Al concentrations lower than that corresponding to the γ TiAl phase (i.e., less than 50 at. %). The reaction mechanism was determined to be diffusion of Al and atomic oxygen from Al_2O_3 into the matrix and the formation of a γ TiAl layer at the Al_2O_3/matrix interface.

Use of Al_2O_3 fibers in γ TiAl-based matrices is not likely to pose any chemical compatibility problems. However, alumina fibers would not be chemically stable in the matrices based on the $Ti_3Al(\alpha_2)$ phase. Of particular concern is the dissolution of atomic oxygen in the matrix, which would adversely affect the mechanical properties of the composite.



Ti_3Al reacted with Al_2O_3 for 24 hr at 1000 °C.

Work is in progress to identify suitable interfacial diffusion barrier coatings for the Ti_3Al/Al_2O_3 composite system.

Bibliography

Misra, A.K.: Reaction of Ti and Ti-Al Alloys With Alumina. Metall. Trans. A, vol. 22, no. 3, Mar. 1991.

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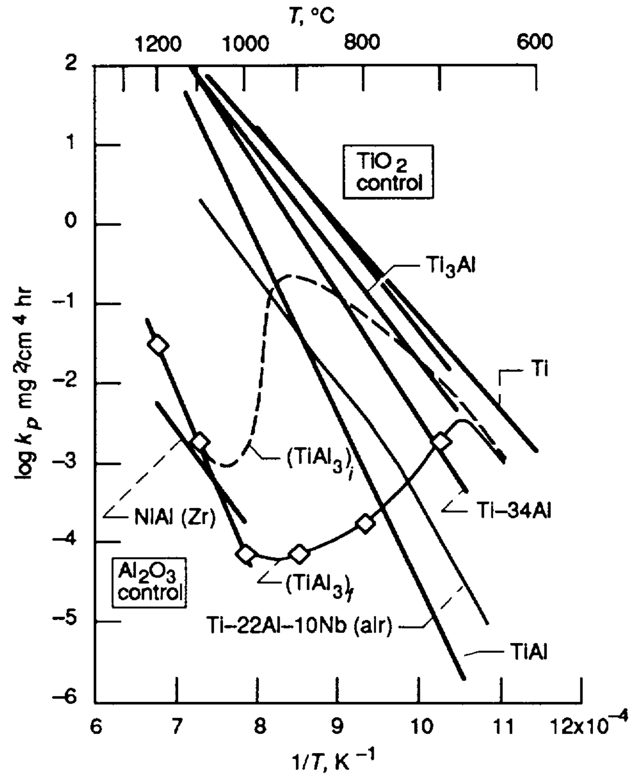
Oxidation of Titanium Aluminides Studied

The development of advanced supersonic and hypersonic aircraft depends in large part on the development of advanced high-strength, lightweight, high-temperature turbine engine materials. Titanium and titanium aluminides represent a class of materials that is about one-half the weight of superalloys and possesses a high strength-to-weight ratio. One of the problems limiting the use of the materials is the poor high-temperature oxidation resistance of titanium alloys, which have even been known to ignite and burn.

As was the case for the nickel-based superalloys currently in use, researchers are now investigating the possibility of oxidation-resistant titanium alloys or coatings for these alloys. One of the fundamental questions to be addressed is whether any TiAl binary alloy is truly oxidation resistant. Oxidation resistance would be achieved if oxidation produced only Al_2O_3 scales that grew at the very low rates typically observed for oxidation-resistant NiAl alloys.

This study performed at NASA Lewis involved the isothermal oxidation of $TiAl_3$ castings in order to determine the growth rates of the scales and the type of scale formed. Weight change was recorded as a function of time for oxidation coupons heated for 100 hr in oxygen at temperatures ranging from 600 to 1300 °C. Oxidation rate was determined from a parabolic growth-rate law which states that the scale thickens proportionally to the square root of time.



Arrhenius plot of parabolic growth-rate constant for TiAl alloys.

The parabolic growth-rate constants for $TiAl_3$ and other TiAl alloys are shown as an Arrhenius plot of log k_p versus $1/T$. Above 1000 °C the oxidation rates do appear to follow those for Al_2O_3 scales formed on oxidation-resistant NiAl alloys. Below 1000 °C the oxidation curves exhibit an initial high rate (dashed line). Also, both rates increase with decreasing temperature. This anomalous behavior was due to the rapid internal oxidation of a continuous second phase of aluminum, which is liquid above 660 °C. As this phase is consumed by interdiffusion with the alloy or by oxidation (high temperature or long times), the rate constants are more in line with the low values for thin Al_2O_3 scales. This troublesome phase was commonly observed in $TiAl_3$ castings by various other investigators. HIPing or preannealing can eliminate the phase but leaves equally troublesome Kirkendall voids in its place.

In all cases the only scale phase formed was Al_2O_3. This is in contrast to the other TiAl alloys, which formed fast-growing mixtures of TiO_2 and Al_2O_3. Therefore, $TiAl_3$ is the only oxidation-resistant compound in the binary TiAl system. This is consistent with the good oxidation resistance of $TiAl_3$ coatings formed on titanium alloys by aluminizing. Other aspects of $TiAl_3$ oxidation, such as scale microstructure and adhesion behavior, are also being examined. The objective is to understand the formation of protective Al_2O_3 scales on titanium alloys in the same context that we understand the oxidation-resistant NiAl and NiCrAl alloys currently being used in turbines.

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Thermodynamic Modeling Assesses Ceramics in Combustion Environments

The High Speed Civil Transport propulsion system has many stringent material requirements. The leading combustor design involves a fuel-rich burn and a fuel-lean burn portion, both of which operate at temperatures above 2500 °F. The high temperatures make ceramic matrix composites (CMC's) the leading material choice. One of the most important issues is the corrosive degradation of these composites by the combustion gases. Therefore NASA Lewis is modeling the degradation of these ceramics.

The leading ceramic systems for this application are silicon-based ceramics (silicon carbide, silicon nitride, molybdenum disilicide, and composites of these); alumina-based ceramics (alumina, mullite, and yttria alumina garnet); and rare-earth-stabilized zirconia systems. The degradation of each of these systems was modeled in both a fuel-lean and a fuel-rich environment. The actual chemical reactions leading to degradation are specific to each system, but in most cases vaporization is a major route.

The modeling procedure involves several steps. First, a maximum material loss rate of 10 mils/10,000 hr (0.025 μm/hr) is established. From this, a maximum possible mass flux is derived that is related to a vapor pressure by means of the mass transport equations. For most systems a vapor pressure of about 6×10^{-9} atm, gives the maximum material loss rate. The vapor pressures of the major species in the gas environments are calculated by a free-energy minimization computer code as a function of temperature. By determining the temperature that gives a vapor pressure of 6×10^{-9} atm, the maximum possible use temperature for each material can be estimated.

For the silicon-based ceramics there are a number of possible degradation routes in these environments. These ceramics are protected by a thin film of SiO_2, and the degradation routes involve disruption of this film. For the fuel-lean environment the major degradation routes are rapid oxidation rates, vaporization of the SiO_2 film, and softening of the SiO_2 film. Of these, vaporization of the SiO_2 film is a key issue and, when the modeling procedure described is used, limits the use temperature to about 2780 °F. For the fuel-rich environment a protective SiO_2 scale is predicted to form, but it may be reduced to SiO(g) by the large amount of hydrogen in the atmosphere. This leads to a predicted maximum use temperature of about 2500 °F.

The alumina-based ceramics generally show the least degradation in these environments. The major route for degradation is vaporization. The modeling procedure gives a limit of about 3630 °F for fully stabilized yttria-zirconia in both the fuel-lean and fuel-rich portions.

This is an ongoing project. Current efforts are aimed at refining the calculations and performing key experiments to test the predictions. This information must be integrated with the physical property and mechanical property requirements to arrive at optimum material systems for the High Speed Civil Transport combustor.

Bibliography

Jacobson, N.S.: Durability Issues for Structural Ceramics in Combustion Environments. Presented

at the 15th Annual Conference on Composites and Advanced Ceramics, Cocoa Beach, FL, Jan. 14–17, 1991.

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Niobium Works as a Compliant Layer for the Ti_3Al/SiC Composite System

The titanium aluminide composite SiC/ Ti_3Al+Nb (Ti–24Al–11Nb, at. %) is currently being considered as a potential high-temperature engine material. The coefficient of thermal expansion (CTE) mismatch between the SiC fiber and the matrix causes large residual tensile stresses to develop in the matrix after the composite has cooled from the processing temperature to room temperature. These residual stresses result in radial cracks in the matrix near the fiber/matrix interface.

The effectiveness of an interlayer of niobium between the fiber and the matrix in reducing or eliminating radial cracking of the matrix has been evaluated for a Ti_3Al/SiC (SCS–6 fiber) composite system. Experiments were conducted in which a single SCS–6 fiber was hot pressed between two Ti_3Al disks with and without the niobium interlayer and the composite was examined after cooling to room temperature for radial cracks near the fiber/ matrix interface.

As expected, large numbers of radial cracks were observed in the matrix near the fiber/ matrix interface for the Ti_3Al/SCS–6 composite without any niobium interlayer. On the other hand, no radial cracks in the matrix were observed for the composite with a niobium interlayer between the fiber and the matrix. The ductile niobium appears to have blunted the cracks.

Reaction of niobium with Ti_3Al at the hot pressing temperature resulted in the formation of a β-phase reaction zone approximately 10 to 12 μm thick. The reaction zone thickness remained more or less the same after long annealing times at lower temperatures (i.e., 800 °C). Niobium also reacted with the SCS–6 fiber at the hot pressing temperature, but the extent of reaction appeared to be small. Studies are ongoing to determine if the reaction between niobium and SiC has any adverse effects on the composite properties. Work is in progress through a contract with Textron Specialty Materials, Inc., of Lowell, Massachusetts, to manufacture Ti_3Al+Nb/ SCS–6 composite panels with the niobium interfacial coating on the fiber.

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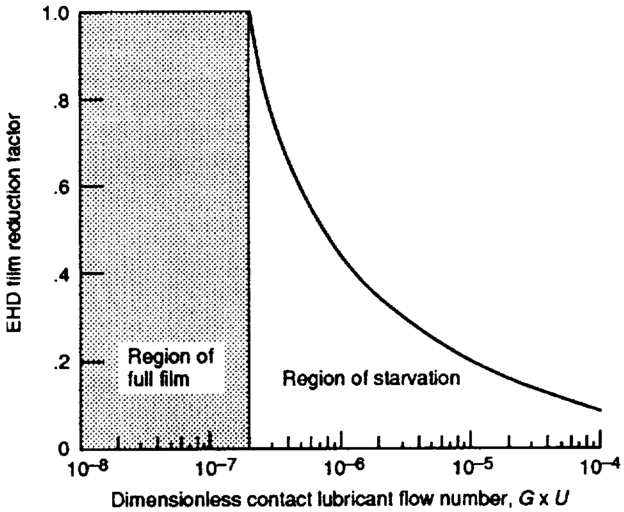
Structures

Bearing Elastohydrodynamic Lubrication Formula Made Simple

The lubricant film separating the moving components in a ball or roller bearing is referred to as the elastohydrodynamic (EHD) lubricant film. The theoretical EHD film thickness is reduced by the lubricant's inability to flow into the bearing contact zone fast enough to supply the volume required to establish this theoretical film thickness. An adequate film thickness is necessary for the successful operation of rolling-element bearings. The proper bearing must be chosen for a particular application so that the appropriate film thickness can be obtained. Calculating this film thickness for the selection process is a complex operation.

NASA Lewis has developed a method that reduces the previous complicated EHD formula to a simplified form that requires only the rolling-element bearing's inside and outside diameters, the speed (in revolutions per minute), the lubricant type, and the lubricant viscosity at temperature (in centipoise). In 1990 a graph was provided for the first time that was based upon experimental data and gave EHD film reduction factor as a function of contact lubricant flow number. This reduction factor accounts for lubricant starvation with the ball or roller-race contact.



EHD film reduction factor as a function of contact lubricant flow number.

By using this corrected EHD film thickness, rolling-element bearing life can be determined with reasonable engineering certainty.

Bibliography

Zaretsky, E.V.: Bearing Elastohydrodynamic Lubrication: A Complex Calculation Made Simple. NASA TM-102575, 1990.

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NASTRAN Improved for Low-Velocity Impact Analysis

A fundamental drawback in using many advanced composite materials in critical load-bearing aerospace structures is their brittle fracture behavior, particularly when subjected to impact loading. Computational tools are therefore required to simulate the initiation and development of impact damage in brittle composite structures. A numerical analysis package has been developed at NASA Lewis that has significantly enhanced the capabilities of NASTRAN in this area.

Damage prediction in an impacted structure requires accurate calculation of local stresses in the region of contact with the impactor. During low-velocity impact a region of nonlinear elastic deformation forms near the impact point, and regions of the structure remote from the impact deform in a linear elastic manner. An accurate, yet computationally efficient impact analysis must therefore couple the linear elastic deformation of the global structure with the nonlinear elastic local deformation near the impactor. A new computational algorithm has recently been incorporated into the NASTRAN finite element analysis program to accomplish this. The result is a greatly simplified impact analysis package, which is available for public distribution through COSMIC at the University of Georgia.

This modified finite element analysis package is used at the Naval Weapons Center and the Johns Hopkins University Applied Physics Laboratory to computationally simulate the dynamic response of composite rocket motor cases to sudden impact loading. It is used at Lewis, for example, to calculate the transient impact force, local contact deformation, and remote strain response in composite structures. Calculated values show excellent agreement with experimental results.

Bibliography

Trowbridge, D.A.; Grady, J.E.; and Aiello, R.A.: Low Velocity Impact Analysis With NASTRAN. 18th NASTRAN Users' Colloquium, NASA CP-3069, 1990, pp. 115-134.

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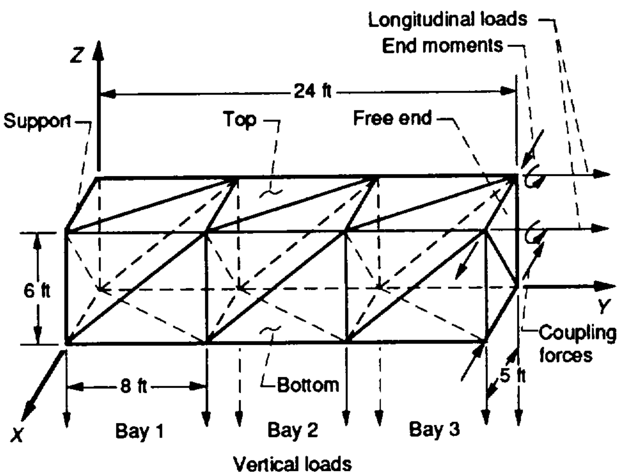
Space Station Structures Analyzed by Probabilistic Structural Methods

Probabilistic structural analysis methods (PSAM) contained in the Numerical Evaluation of Stochastic Structures Under Stresses (NESSUS) computer code are being used at NASA Lewis to analyze typical trusses that will be used in the design of the space station.



Typical truss in solar array panel mast.

It is a common practice to evaluate the structural integrity of trusses with the aid of deterministic analysis techniques and appropriate load or safety factors. However, PSAM considers the various uncertainties in a formal quantitative manner rather than as either single values or upper and lower bound values. A truss is probabilistically analyzed by defining the primitive design variables, such as spatial truss geometry, stiffness parameters, applied loads, and moments, which are described in terms of probability density functions. The cumulative distribution functions for the response functions and the sensitivities associated with the primitive variables for given responses are investigated. The probabilistic structural responses indicate substantial scatter in natural frequencies and in some member axial forces but show less scatter in the displacements.

These methods have a prominent role in designing complex structural components because they can consider various uncertainties in the design variables and thus ultimately may prevent unanticipated failures.

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Transverse Crack Detection in Composites Improved

The use of ultrasound to obtain images of flaws or damage in polymer composite laminates is well established and quite effective. In a common procedure, called C-scan, an ultrasound transducer scans an area of the laminate. The amount of energy transmitted through the laminate (through-transmission method) or reflected back from the laminate (pulse-echo method) is displayed to produce an image that shows flaws or defects. This technique is particularly effective in detecting debonding between plies of the laminate. However, cracks that occur through the thickness are not easy to detect, since the waves propagate parallel to the crack, often leaving them undetected. Transverse cracks are important because they are often the first type of damage to occur as a result of either thermal or mechanical loading. A modified C-scan technique that uses oblique shear waves was developed at NASA Lewis to improve the detection of these transverse cracks. Normal longitudinal waves are used with the standard method.

When a longitudinal wave traveling in a fluid is incident at an angle on an anisotropic solid, such as a composite laminate, three types of waves are typically generated in the solid. These waves are termed quasi-longitudinal (QL), vertically polarized quasi-shear (QSV), and horizontally polarized quasi-shear (QSH) waves. In the technique developed at Lewis, the incident angle is calculated such that the QL waves are completely reflected from the solid and QSH waves are not generated. The remaining QSV waves, which are transmitted through the laminate at an oblique angle, are used to detect the presence of transverse cracks. An advantage of this technique is that it can be used with very little modification to standard C-scan equipment.

Initial results have shown that this technique is more effective in detecting transverse cracks than the standard procedure. It is being used in an ongoing research project to measure damage progression in polymer composites.

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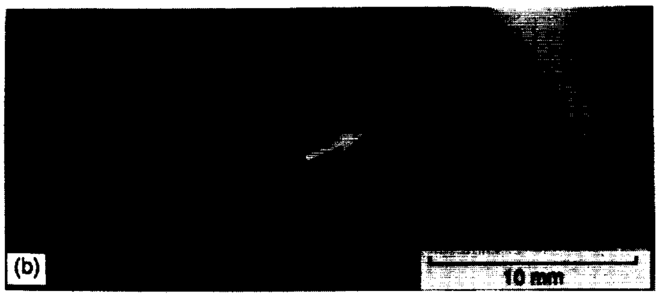

(a) Normal through-transmission.
(b) Oblique shear wave transmission.

Images of a transverse crack in a 60 ° off-axis unidirectional sample taken by the two types of C-scans. The shear wave technique produces an enhanced image. Arrows indicate the location of the crack.

Bibliography

Pereira, J.M.; and Generazio, E.R.: Improved Transverse Crack Detection in Composites. NASA TM-103261, 1990.

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Micromechanical Tailoring and Fabrication Optimized Concurrently for Metal-Matrix Composites

The development of residual stresses in metal-matrix composites (MMC's) during their fabrication has adverse effects on critical properties, such as strength and thermomechanical fatigue life. Hence, the residual stresses limit the applications of MMC's as high-temperature materials and offset many of their other advantages. Although the residual stresses cannot be eliminated, their control or reduction seems possible, either by altering fabrication parameters or incorporating a fiber/matrix interphase material. In order to obtain full benefits from this approach, a method has been devised at NASA Lewis that optimizes concurrently the fabrication of MMC's and the thermomechanical properties of a fiber/matrix interphase. The objectives are to control the development of residual microstresses and avoid failures in the fibers, the matrix, and the interphase throughout the process.

The thermomechanical response of the composite during fabrication is simulated by using nonlinear micromechanics contained in an in-house computer code called METCAN (Metal Matrix Composite Analyzer). The theory incorporates, among other factors, three material phases (fiber, matrix, and interphase), temperature and inelastic effects on the constituents, and the residual stress buildup. The optimization is numerically accomplished by nonlinear mathematical programming using the feasible directions method. The method is encoded into another in-house code called MMLT (Metal Matrix Laminate Tailoring).

The method was evaluated by using it to minimize the matrix residual stresses of an ultra-high-modulus graphite (P100)/copper composite. The following two cases were investigated: (1) the individual optimization of the fabrication process and (2) concurrent optimization of the fabrication process and the interphase properties. The resultant optimal fabrication processes with and without interphase tailoring indicated similar trends. The most significant trend was the gradual, but significant, increase in consolidation pressure as the temperature decreased, which contributed to the reduction of the residual matrix microstresses. All residual thermal strains were forced to develop when the matrix and the interphase were highly nonlinear, such that high thermal strains induced low thermal stresses.

The importance of a compatible tailored interphase was also demonstrated. The concurrent fabrication-interphase tailoring reduced the longitudinal and transverse matrix stresses by 41 and 24 percent, respectively; fabrication optimization alone reduced these stresses by 21 and 0 percent only.

It is expected that both the obtained results and the computer code, still under development, will have a definite impact on the development of high-temperature composites.

Bibliography

Morel, M.R.; Saravanos, D.A.; and Chamis, C.C.: Micromechanical and Fabrication Processes Optimization for Advanced Metal-Matrix Composites. Proceedings, Structural Engineering and Optimization, J. Zarka and O. Ohtmer, eds., 1990, pp. 245–254. (Also NASA TM-103670.)

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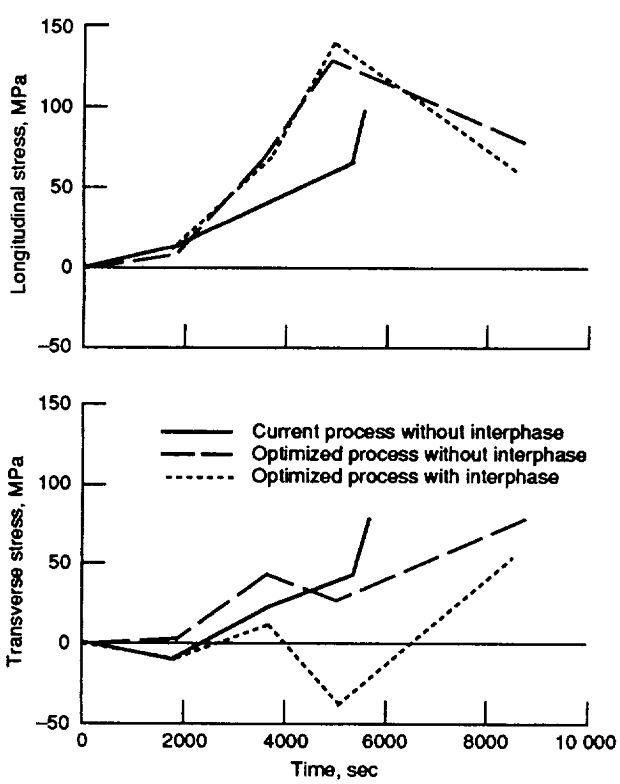


Predicted residual stress development for P100/copper.

Ultrasonic Theory and Experimental Technique Developed to Nondestructively Evaluate Ceramic Composites

Composite materials with low densities and good high-temperature properties are being developed for use in the next generation of aerospace systems. Both the National Aero-space Plane (NASP), a transportation system that will take off like a conventional aircraft, fly at Mach 25 directly into orbit, and land like a conventional aircraft, and the High Speed Civil Transport (HSCT), an aircraft that will transport 250 passengers at Mach 3.2 for 5000 n mi, will require advanced composite materials for propulsion and structural components.

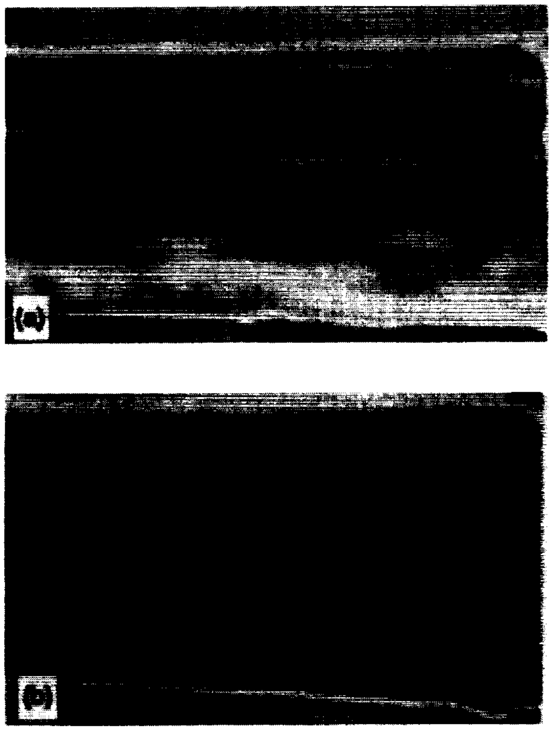
The strength and toughness of ceramic composites are limited by the degree of bonding between the fiber and the matrix material. Unfortunately, the only way to determine the quality of this bond has been by destructive testing. However, a nondestructive technique called angular power spectrum scanning (APSS) has been developed at NASA Lewis that makes use of the sensitive interaction of ultrasound with the pores, fibers, and grains which make up these ceramic composites.

To nondestructively evaluate composite materials, we need to understand the interaction of ultrasound with each of the scattering components in the composite. Ultrasonic scattering mechanisms for ceramic composites have been identified by examining the interaction of ultrasound with individual fibers, pores, and grains. The dominant ultrasonic scattering mechanisms for ceramic composites are

(1) Symmetric diffractive scattering at individual pores
(2) Symmetric diffractive scattering at the fiber/matrix interface
(3) Asymmetric refractive scattering at density gradients in the matrix material

Grain boundary scattering in the matrix material has been found to be negligible for both SiC and Si_3N_4.

The new nonintrusive ultrasonic evaluation technique, angular power spectrum scanning, takes advantage of the symmetry of the scattering mechanisms. APSS uses a



(a) Before thermal cycling. (Bands are caused by good fiber/matrix bond.)
(b) After thermal cycling. (Missing bands indicate degradation in bond quality.)

APSS ultrasonic images.

collimated ultrasonic beam directed at one side of a composite sample. The ultrasonic energy is measured as a function of the half-solid angle on the other side of the sample. The energy as a function of angle and constant-energy contours can be obtained at each point on the sample.

Composites having a uniform microstructure yield symmetric angular power spectrums. Any asymmetry in the observed angular power spectrums indicates the presence of porosity gradients. Diffractive patterns created by the interaction of ultrasound with the fiber and the fiber/matrix interface can be used to identify variations in bond quality throughout the bulk of the material. This information is not available by any other nondestructive technique.

Bibliography

Generazio, E.R.: Theory and Experimental Technique for Nondestructive Evaluation of Ceramic Composites. NASA TM-102561, 1990.

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Computed Tomography Guides Machining and Structural Modeling

Metal-matrix composites (MMC) are being developed to provide gas turbine engine components that can be used at temperatures of 425 to 1315 °C. Before full-scale MMC structures can be made, subscale engine components must be prototyped, and related life prediction analyses must be performed and experimentally verified. Further, nondestructive evaluation (NDE) technologies must be explored in concert with the different fabrication methods and the complex geometric nature of the finished product. Consequently, Pratt & Whitney Aircraft and NASA Lewis, under a nonbinding cooperative program, are studying a silicon-carbide-fiber-reinforced, titanium-metal-matrix composite system (SCS–6/Ti–15V–3Cr–3Al–3Sn) for the manufacture of three subscale rings. The activities include life prediction systems, NDE, and processing aspects. The work highlighted herein is part of the NASA NDE activity.

Computed tomography (CT) with 250- to 350-μm resolution provides three-dimensional density information for metal-matrix composite subscale engine components. In tests of the subscale rings CT cross-sectional density information differentiated between the monolithic case and the composite core. Density variations imaged in the composite core were due to poor consolidation, fiber bunching, and poor bonding. The distortion of the composite core and its closeness to the top edge of the ring were due to fabrication and tooling problems. CT can help locate the composite core before final machining to prevent machining through the fibers. Identification of the precise three-dimensional geometry and

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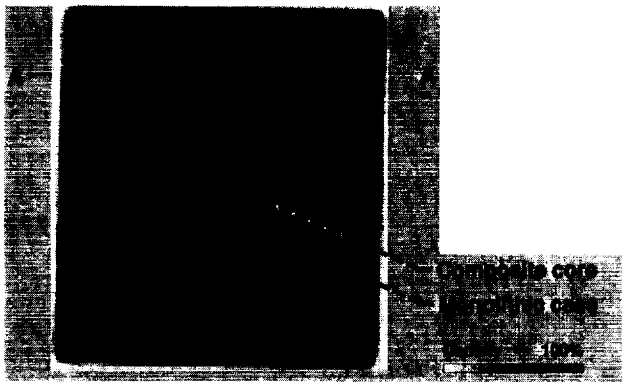

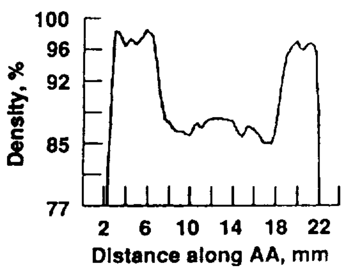

Cross-sectional slice of NASA/P&W MMC ring.

density of both the monolithic case and the composite core can aid in developing more realistic finite element models for stress analysis and life prediction of MMC engine components.

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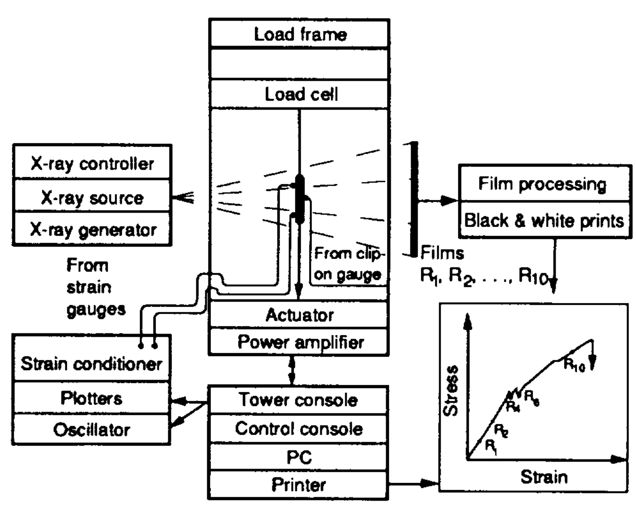
In-Situ X-Ray Radiography Images Damage Accumulation in SiC/RBSN Tensile Specimens

Ceramic-matrix composite (CMC) systems are being developed for heat engine applications. The ultimate goal of current research is an understanding of composite behavior in order to better optimize the composite properties for different hot-section applications. CMC's are being developed because they provide enhanced material toughness while maintaining the useful properties of monolithic ceramics. In order to use CMC's more effectively, their failure processes and damage tolerances must be understood and, in turn, their failure analysis and mechanics models must be improved. In-situ x-ray radiography can help by imaging the failure sequences and damage accumulation in composite specimens under loading. The information gathered from such in-situ monitoring can help in the development and validation of analytical models and in the coordination between experiment and theory. Damage and failure mechanisms (e.g., transverse matrix cracking, fiber/matrix debonding, fiber breaking, fiber pullout, and delamination) can be better understood if they are imaged and identified as they occur. Such in-situ examination will help identify and clarify the sequence in which these mechanisms take place and consequently aid in identifying deformation-controlling properties (i.e., whether they are matrix-dominated properties, fiber-dominated properties, or a combination of both).

An in-situ x-ray and materials testing system (IX–MTS) was developed to monitor materials under loading. The IX–MTS can monitor damage accumulation in silicon-carbide-fiber-reinforced, reaction-bonded silicon nitride (SiC/RBSN) composite specimens and can determine interfacial shear strength between the SiC fiber and the RBSN matrix by the matrix crack spacing method. The IX–MTS has been used to study the effect of local



Schematic diagram of in-situ x-ray and materials testing system (IX–MTS).

density variations on the fracture behavior of composites and will be used to study thermal and oxidation effects on the interfacial shear strength of composites. This approach can provide a basis for interpretation of mechanical tests, for validation of analytical models, and for verification of experimental procedures.

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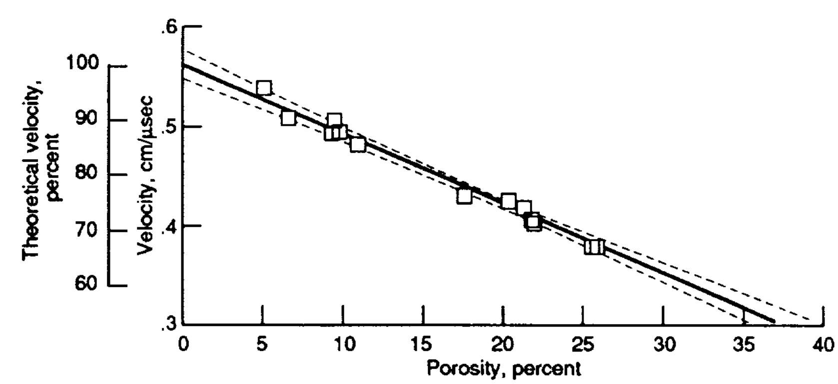
Ultrasonic Measurement of Material Pore Fraction Modeled and Analyzed

The physical behavior of many technologically important polycrystalline materials can be affected by the volume fraction of "holes," or pores, present. For example, pore fraction has been shown to affect (1) the strength, toughness, and modulus of structural and refractory materials, such as steel, tungsten, SiC, Si_3N_4, and Al_2O_3, (2) the strength of nuclear fuel materials such as UO_2, (3) the thermal shock behavior and strength of porcelain-based ceramics, (4) the dielectric and elastic properties of piezoelectric materials, such as PZT, and (5) the critical current density, diamagnetic response, and modulus of superconducting ceramics such as $YBa_2Cu_3O_{7-x}$. Pore fraction variations on the order of 1 percent in $YBa_2Cu_3O_{7-x}$ samples can result in an order-of-magnitude variation in critical current density. Where physical properties are directly dependent on the pore fraction, the measurement of pore fraction becomes important in the quality assurance process for the material. Although various methods are available for measuring the pore fraction of polycrystalline materials, some are limited to certain geometries and others are destructive. The ultrasonic velocity method of measuring pore fraction in polycrystalline materials may be useful and convenient in certain laboratory and industrial situations. NASA Lewis has modeled and analyzed the use of ultrasonic velocity as a measure of pore fraction in polycrystalline materials.

Ultrasonic velocity is a relatively simple measurement that requires the material specimen to have one pair of flat and parallel sides. The advantages of this method are that it is nondestructive and that measurements can be made on different regions of a component to map porosity variation.

The semiempirical model developed showed a linear relationship between ultrasonic velocity and pore fraction in polycrystalline materials. Linear regression correlation coefficients with magnitudes greater than 0.95 (indicating a good correlation) were obtained in 31 out of 42 scatter plots of velocity versus pore fraction. Predicted intercepts (theoretical velocities) and slopes (ratio of change in velocity to change in pore fraction) differed from material to material as expected, since each material has different elastic constants and theoretical density. The values of theoretical velocity predicted from regression and those calculated



Longitudinal velocity versus percent porosity for $YBa_2Cu_3O_{7-x}$

from elastic properties agreed within approximately 17 percent in 16 out of 16 cases and within approximately 6 percent in 11 out of 16 cases. Batch-to-batch, sample-to-sample, and within-sample pore fraction variations for a material can be estimated if the velocity–pore fraction relation is known with reasonable confidence for that material.

Bibliography

Roth, D.J., et al.: Review and Statistical Analysis of the Ultrasonic Velocity Method for Estimating the Porosity Fraction in Polycrystalline Materials. NASA TM-102501, 1990.

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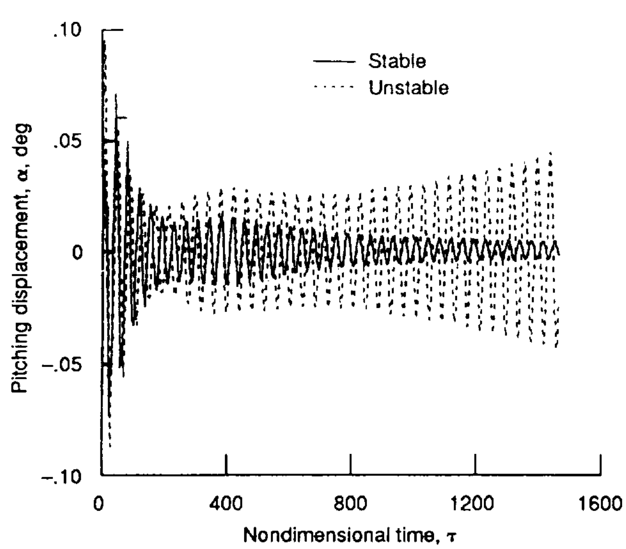
Full Potential Solver Used for Time-Domain Flutter Analysis of Cascades

The traditional approach to calculating the flutter of bladed disks (stators and rotors) has been the frequency-domain analysis. The aerodynamic forces that are typically used with this approach are based on a linear potential theory which neglects the effects of blade loading due to thickness, camber, and angle of attack and is not suitable for transonic flows. At NASA Lewis the unsteady full potential equation has been used as the basis for a two-dimensional cascade flow model that can represent flows over a wide range of Mach numbers from low subsonic to supersonic, including transonic flows with weak shocks.



Blade motions at stable and unstable conditions for cascade geometry representative of SR5 propfan.

In the time-domain method of flutter analysis the equations of motion for the blades are integrated simultaneously with the full-potential equation governing the inviscid, irrotational fluid flow. Starting with the steady flow field, one blade in the cascade is given a small disturbance in the form of a pitching velocity. The variation of blade pitching and plunging displacements with time is used to determine the stability of the cascade. The blade motions either decay or grow with time, depending on the reduced flow velocity, indicating stability or instability, respectively. The main benefits of the time-domain approach are the ability to handle nonlinear structural models and aerodynamic forces that are nonlinearly dependent on blade displacements. The time-domain approach allows a realistic simulation of the motion of the fluid and of the cascade blades for a better physical understanding.

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Global Approach Identifies Structural Joint Properties

Joints usually contribute significantly to the overall system stiffness, damping, and in many cases nonlinearity. Therefore, it is critical that reliable joint models be made available. For many structural systems the constituent components often can be modeled accurately, but the joints contain considerable modeling uncertainty. Therefore, accurate system response predictions often are highly dependent on valid joint models.

NASA Lewis has developed a global approach for identifying the properties of structural joints. The procedure, which uses experimental response data, is considered general because it is applicable to any size or type of structural system. Furthermore, characteristics such as damping and stiffness, as well as nonlinearities in joints, can be identified.

This global approach is applicable to both linear and nonlinear joints and is suitable for processing test data measured at arbitrary stations on the structural system. The approach identifies joint parameters by performing a "global" fit between the predicted and measured data. The approach improves on previous methods because it can better deal with parameter-dependent constraints (e.g., gaps).

The approach was demonstrated with a friction-damped bladed disk assembly. This assembly is a relatively complex system that exhibits considerable joint damping. For typical bladed disk assemblies the dominant joint damping originates from blade tip rubbing or from interblade friction forces acting at the blade's shroud locations.

In order to identify the connection parameters, the complete structural system was excited at various stations along the structure, and the resulting response (e.g., displacements and velocities) was measured. The measurement stations may, or may not, be collocated with the excitation, and the number of measurement stations may, or may not, be equal to the number of input excitations. In general, it was simpler to excite the system with a single input and then measure the resulting response at multiple stations. It is required that the input be known and the output be measured, regardless of the number of stations. The response measurements need not be stationed directly at the connection bound-aries but instead may be established at any convenient position on the system.

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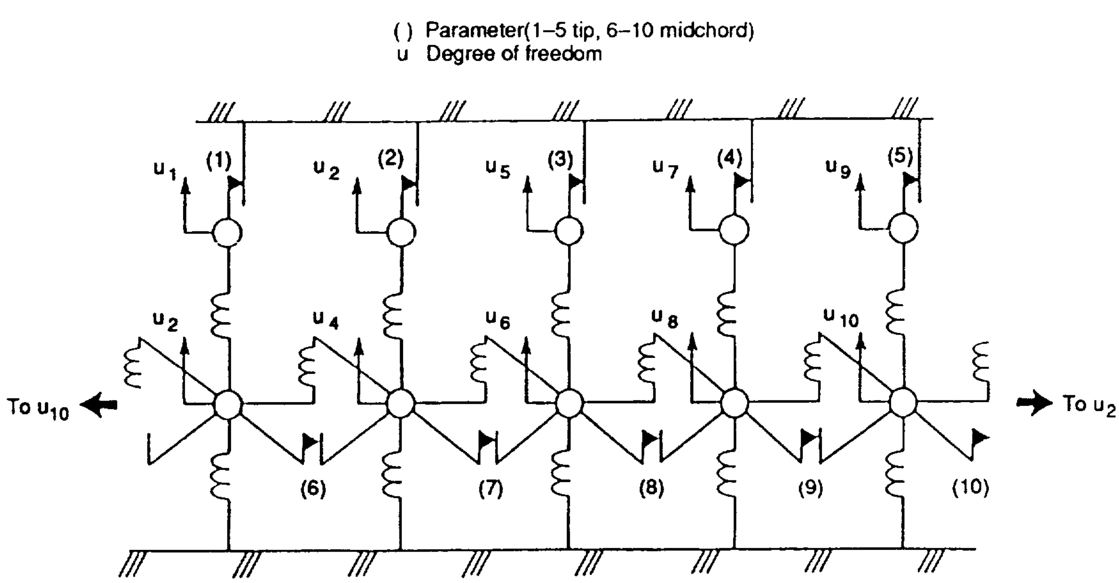
Counterrotation Propfan Unstalled Flutter Experimentally Investigated

Propfans may have unstalled flutter in their operating range. The thin airfoil sections, high blade sweep, high solidity, low aspect ratio, and transonic to supersonic tip speeds of propfans give them this potential. Unstalled flutter has been investigated experimentally for single-rotation propfans and has



Bladed-disk assembly model.

F21/A21 counterrotation propeller model in wind tunnel.

guided the development of flutter analyses. A shift in interest to counterrotation required a similar investigation for this configuration. Therefore an experiment was planned and conducted using a counterrotation propfan model with a front rotor that had flutter. The objectives were to study the characteristics of the flutter and the effect that the aerodynamic interactions between the rotors had on it.

The model, called F21/A21, was installed in the Lewis 8- by 6-Foot Supersonic/Transonic Wind Tunnel. There were 13 blades on the front rotor and 10 blades on the rear rotor. The rotor diameters were nominally 2 ft. First, the front rotor was tested alone to map its stability. Then both rotors were tested, with the rear rotor at different powers, and the front rotor stability was remapped to see the change. In general, the aft rotor slightly increased the stability of the front rotor—a small but favorable effect of rotor aerodynamic interactions. The stability of the rotor decreased when blade setting angle was increased, and flutter occurred in several modes over the range of the test conditions. In addition to conventional strain gages, a laser-based optical system was used to obtain measurements at flutter. The laser data provided detailed spectral results, phases between all the rotor blades, and a measurement of the flutter mode shape at the blade section cut by the laser beam.

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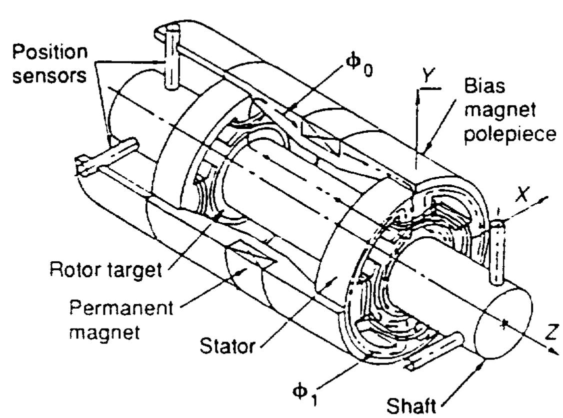
Hybrid Magnetic Bearing Developed for Cryogenic Applications

A new magnetic bearing has been designed and fabricated by Avcon Incorporated under contract to NASA Lewis. This bearing is called a hybrid magnetic bearing with permanent magnet bias because it contains both permanent magnets and electromagnets. This new concept has the advantages of reduced size, weight, and electrical power consumption over magnetic bearings currently used in industry. These features make this bearing very attractive for aerospace applications. The bearing was designed for possible use in future space shuttle main engine turbopumps.

Conventional magnetic bearings employ only electromagnets to achieve suspension and control of rotors. They require large amounts of electric power at all times to suspend the rotor and to produce a bias magnetic flux. The bias magnetic flux linearizes the force-to-current relationship of the bearing and thus simplifies the bearing control system. In the hybrid magnetic bearing the permanent magnets provide the bias magnetic flux so that electric power is not required to perform this function. The electromagnets use only a small



Hybrid magnetic bearing with permanent magnet bias.

amount of electric power to keep the rotor centered in the presence of random disturbances and to counter any high dynamic forces on the rotor. Hybrid bearings use much less electric power than conventional magnetic bearings.

In previous permanent magnet bias bearings the electromagnet flux had to pass through the permanent magnets, an inefficient use of the electromagnet flux. In this new concept the permanent magnets are not in the electromagnet flux path so that the efficiency of the electromagnets is not compromised. The permanent magnets are arranged to produce flux lines along the rotor axis, whereas the electromagnet flux lines are circumferential.

The hybrid magnetic bearing designed under this contract has a radial load capacity of 500 lb. The bearing has a 3.0-in. air gap diameter, a 5.25-in. stator outside diameter, and a 4.12-in. length. The bearing was installed into an existing rig capable of operating up to 15,000 rpm. The speed is limited by the rig, not by the magnetic bearing.

Preliminary tests of the bearing have been performed at room temperature for radial loads up to 400 lb, stiffness up to 100,000 lb/in., and speeds up to 9800 rpm.

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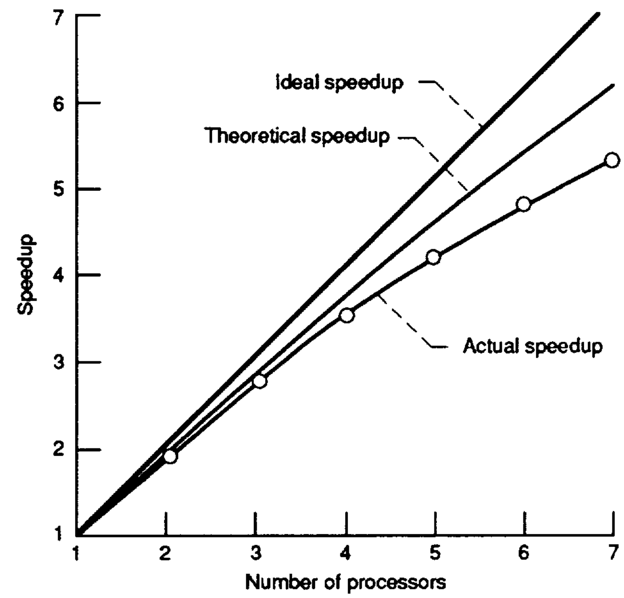
Aeroelastic Analysis of Propfans Adapted for Concurrent Processing

Propfans offer significant fuel savings (30 to 50 percent) over current turbofan engines for the next generation of transport aircraft. A propfan is a radically new aircraft propeller that can operate at the high flight speeds of turbofan engines. Unlike conventional propellers, propfans have thin, flexible blades that undergo large deflections and have large



Execution time performance of parallel processing for propfan aeroelastic analysis.

variable sweep. Analysis programs have been developed to predict, and thus avoid, aeroelastic instabilities, which can lead to catastrophic failure of propfan blades.

An advanced aeroelastic analysis program was adapted to run efficiently on a shared-memory multiple processor computer, an Alliant FX/80. The program, ASTROP3, uses a three-dimensional, compressible, unsteady aerodynamic model and blade normal modes to calculate the aeroelastic stability and response of propfan blades.

Within ASTROP3, the major amount of execution time is used in the computation of aerodynamic influence coefficients. In a representative case with a model of the SR3C-X2 propfan blade, the coefficient computation used 97 percent of the total execution time. Fortunately, this computation is highly independent and thus can be done concurrently on separate processors.

For efficient execution in a parallel processing environment, the overhead time involved in setting up for vector and concurrent processing must be minimized. Overhead can be controlled by selective use of compiler options and directives to enable vectorization or concurrentization only where a reduction in execution time will result. In the ASTROP3 code, changes were made to enable the concurrentization of the entire influence coefficient computation. Further modification rescheduled the parallel subtasks such that idle time of available processors was reduced.

Speedups attained on the Alliant FX/80 using different numbers of processors were recorded for the flutter analysis of a SR3C–X2 propfan rotor and compared with ideal and theoretical speedups. For seven processors the actual speedup was 5.28, or 75.4 percent of ideal.

Bibliography

Murthy, D.V.; and Janetzke, D.C.: Concurrent Processing Adaptation of Aeroelastic Analysis of Propfans. AIAA Paper 90–1036, April 1990. (Also NASA TM–102455.)

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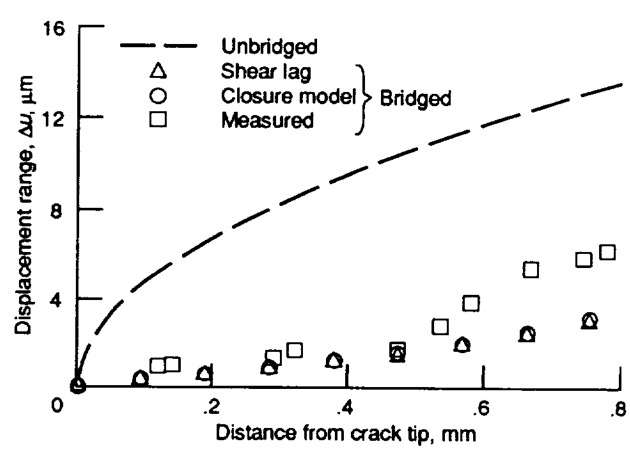
Crack Bridging in Metal-Matrix Composites Modeled Analytically

The ability to predict fatigue crack growth behavior of metal-matrix composites (MMC's) is of particular interest because these materials contain many crack-like defects. These cracks propagate and coalesce under cyclic loading and result in sudden catastrophic fracture. Experimental studies on a number of MMC's have shown that cracks tend to propagate in the ductile matrices, leaving behind unbroken fibers bridging the facing crack surfaces. Crack bridging by fibers has been shown to decrease the crack growth rates by decreasing the near-crack-tip displacements. Understanding crack growth behavior in MMC's is paramount to the development of accurate life prediction models for composite structures. Future NASA missions will depend upon our ability to use MMC's in reusable structural applications, where durability is essential for success.

Crack bridging has been analytically modeled to determine its effects on fatigue crack propagation rates and crack opening displacements. The phenomena are complex and modeling efforts are difficult. Nevertheless, NASA Lewis has a strong continuing commitment to solve these vexing problems. The material modeled is a silicon-carbide-fiber-reinforced Ti–15–3–3–3-matrix MMC. Two different models were used to simulate crack bridging. The first model was the so-called shear lag model. This model is based on the relative sliding between the fiber and the matrix in the region where the interfacial shear stresses exceed the frictional shear stresses. The second model was the newly formulated fiber pressure model. This model assumes that the decrease in the crack driving force due to bridging is proportional to the normal and bending forces carried by the fibers.

The analytical results for both models were compared with experimental data obtained from tests performed in a specially designed loading stage mounted inside a scanning electron microscope. Use of this facility allowed for very precise measurements of crack opening displacements and crack growth rates. The experimental results revealed a decrease in crack growth rates with an increase in the crack length.

Both models were successful in describing the fatigue crack growth behavior of this MMC in terms of a calculated effective crack driving



Analytical and experimental confirmation of beneficial crack bridging.

force ΔK_{eff}. Also, both models accurately predicted crack opening displacements as well as the experimentally observed decrease in the crack growth rates and the eventual crack arrest. The advantage of the fiber pressure model is that it requires substantially less computing time than the shear lag model. Also some of the material properties needed to run the shear lag model are difficult to obtain.

Improved crack bridging models permit more accurate life prediction modeling for structural components made of MMC's.

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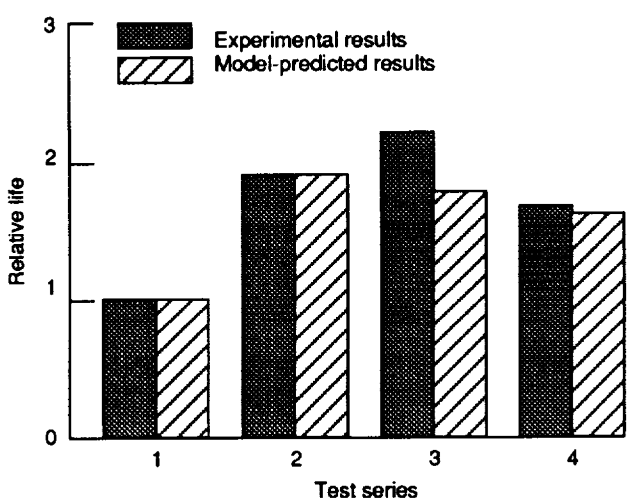
High-Temperature Fatigue Modeled for a Tungsten/Copper Composite

Fatigue failure of high-temperature, metal-matrix composites (MMC's) is a complex process and is a subject of current intense research activity at NASA Lewis. Matrix cracking, fiber/matrix interfacial failure, and fiber fracture work together to result in fatigue failure. However, depending on the failure process of the composite system of interest, a dominant failure mode can be identified. Modeling of dominant failure modes can serve as the basis of fatigue life prediction schemes for MMC's. Future NASA missions will require accurate predictions of MMC structural life.



Validation of MMC life prediction model for tungsten/copper.

A tungsten-fiber-reinforced, copper-matrix composite is a candidate material for rocket nozzle liner applications. Previous research on the fatigue behavior of a 10-vol % tungsten/copper composite at high temperatures had shown that the composite fails primarily due to copper-matrix degradation. Fatigue cracks initiate and propagate inside the copper matrix through a process of initiation, growth, and coalescence of grain boundary cavities. The ductile tungsten fibers "neck down" locally and rupture after the surrounding matrix fails. Complete failure of the composite then ensues.

A fatigue life prediction model for the tungsten/copper composite system has been developed at NASA Lewis. The model is based on microscope-observed failure mechanisms. The composite is assumed to fail when the matrix fails. The failure mechanisms of the fiber and its contribution to the overall composite fatigue life are neglected. It is assumed that no interfacial debonding or degradation occurs. The analysis is limited currently to isothermal fatigue of a unidirectional composite.

In the model the composite is assumed to fail when the average cavity in the matrix reaches a critical size. The cavity nucleation process in the copper matrix is neglected by assuming the preexistence of cavities in the as-received composite. This assumption was confirmed through metallographic examinations. In addition, available literature indicates high-temperature cavity nucleation to be very fast relative to cavity growth. All cavities are assumed to begin to grow at the moment of load application, all at the same rate. The average cavity growth size as a function of time is calculated by using a creep-cavity growth law. It is assumed that cavities grow with a quasi-equilibrium shape controlled by coupled diffusion and plasticity. Spatially averaged instantaneous stresses and strain rates in the matrix were used to calculate cavity size. The average matrix stress is based on an isostrain condition between the fibers and the matrix.

The model-predicted fatigue lives were compared with the experimental results of a series of load-controlled, tension-tension fatigue tests conducted at 560 °C on 10-vol % tungsten/copper. Predicted lives were in agreement with the experimental results. The numerically calculated cavity size was found to vary with cycle number like the experimentally observed cyclic change of the composite maximum tensile strain.

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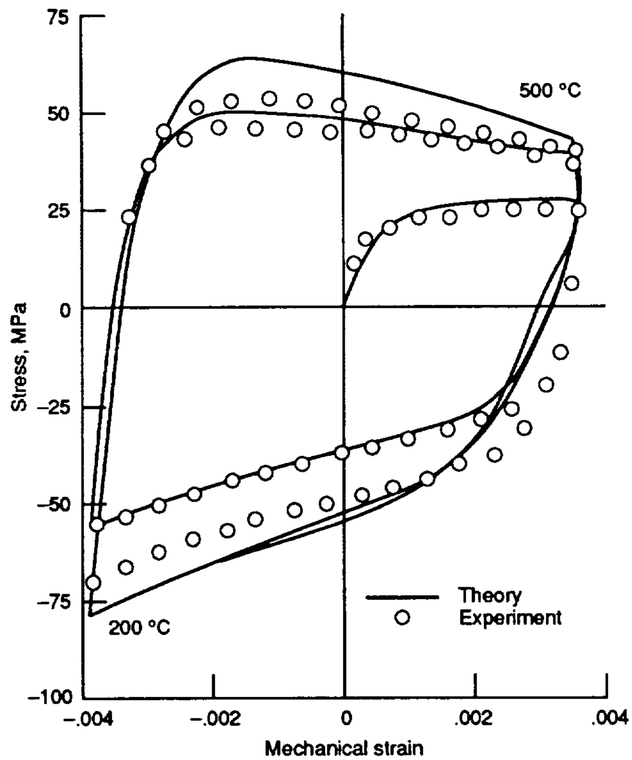

Viscoplastic capability, theory versus experiment.

Developments Made in the Physics of Viscoplasticity

The theory of viscoplasticity is used to describe the deformation behavior of crystalline solids (e.g., metals) brought about by thermal and mechanical loadings. This theory had its origin in the early 1900's. Over the last two decades, the theory has undergone rapid development—in part because of the availability of computers to solve the complex system of differential equations that defines viscoplasticity. For the most part this development has been phenomenological. At NASA Lewis a concentrated effort has been under way for nearly 10 years to replace some of this phenomenology with physics in the hope of simplifying the model and improving its predictive capability. Much has been accomplished toward this goal.

An important aspect of viscoplastic physics is the development of a thermodynamically admissible viscoplastic theory. NASA Lewis and the Office National d'Etudes et de Recherches Aérospatiales (ONERA) in Châtillon, France, formed a cooperative agreement involving exchanges of personnel for the purpose of addressing this and other issues. Four cooperative research projects have been completed as a consequence, with the result being an enhanced understanding of viscoplastic thermodynamics.

Another important area of viscoplastic research is defining how the internal state variables of the theory evolve. Our concentration here has been in simplifying these equations from the point of view of material characterization. An approach has been put forth that enables the viscoplastic theory to analytically reduce to classical creep theory in the steady-state limit. This has simplified the theory and furthered its physical foundation.

A final area of research that has been undertaken at NASA Lewis for the advancement of viscoplasticity is the development of new and improved algorithms for the numerical integration of the viscoplastic constitutive equations. This is of particular importance in nonlinear finite element analyses, where the bulk of the supercomputer's computation time is taken up by numerical integration of the constitutive equations. Preliminary studies indicate computational improvements by as much as a factor of 30 over conventional methods, and this is accomplished with an improvement in accuracy. These results have important ramifications for the magnitude and complexity of structural analyses that can be undertaken in support of NASA missions.

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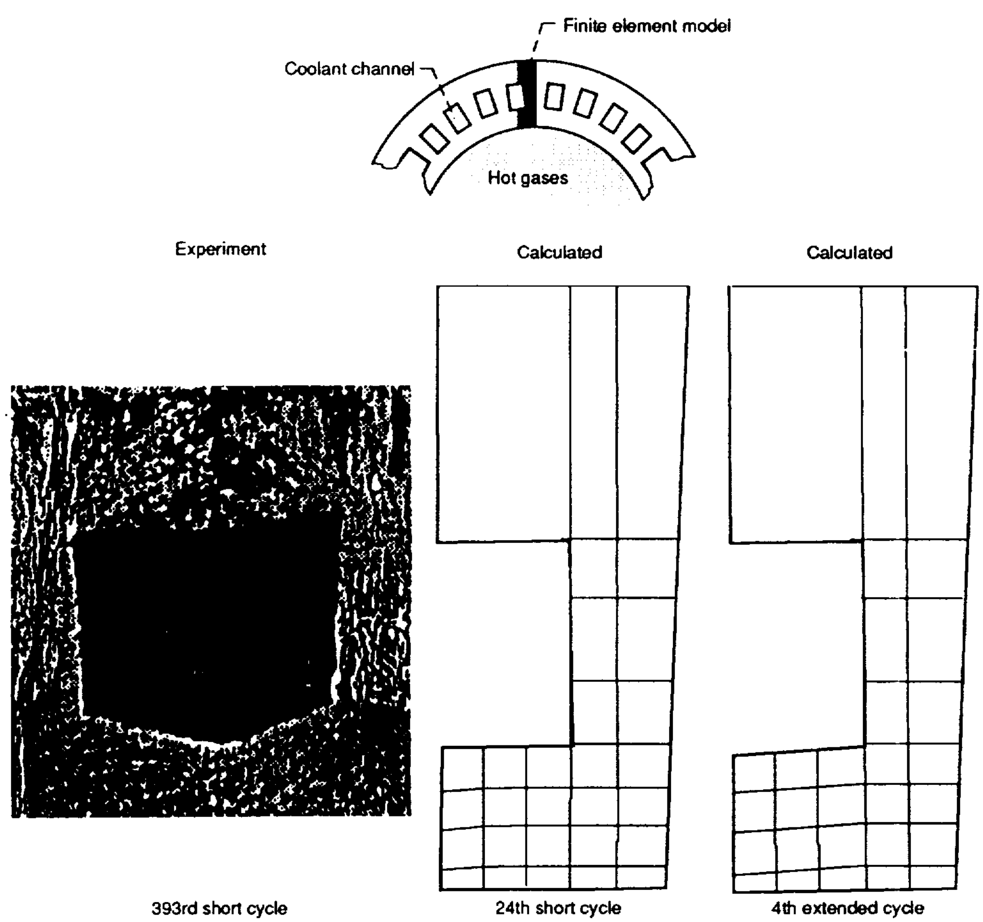
Viscoplastic Analysis Performed for Rocket Thrust Chamber

Combustion gases in rocket thrust chambers such as those in the space shuttle main engines are very hot and are under high pressure. The copper material that lines the inner wall of these chambers is exposed to 6000-psi gases at temperatures of 6000 °F during firing and to cryogenic temperatures during startup and shutdown. The severe thermal and mechanical loads during each rocket firing permanently deform the liner material. Repeated firings result in undesirable distortion and eventual thinning and cracking of the thrust chamber liner near the internal coolant channels. Ongoing research is attempting to develop a better understanding of this durability problem in order to pave the way for developing more durable materials and structural designs.

A viscoplastic stress-strain analysis of an experimental cylindrical rocket thrust chamber has been performed at NASA Lewis by Dr. Vinod Arya of the University of Toledo (Cooperative Agreement NCC3-120). A finite element solution methodology developed at NASA Lewis was employed to perform the viscoplastic analysis. A viscoplastic model has been put forth by Prof. David Robinson of The University of Akron. It incorporates a single internal state variable that represents kinematic hardening. This model was employed to investigate whether such a viscoplastic model could predict the experimentally observed behavior of the thrust chamber.



Viscoplastic predictions of cyclically deformed thrust chamber.

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Two types of loading cycles were considered; a short cycle of 3.5-sec duration that corresponds to the experiments, and an extended cycle of 485-sec duration that is typical of the space shuttle main engine operating cycle. The analysis qualitatively replicated the deformation behavior of the component as observed in experiments at NASA Lewis. It predicted the thinning of the coolant channel wall. And it indicated that the mode and location of failure in the component depends on the duration of the loading cycle—an important implication for future thrust chamber experiments. Advanced viscoplastic analyses have become an essential tool for the realistic life assessment of thrust chambers.

Currently, research is being pursued to investigate how employing metal-matrix composites affects the deformation behavior and service life of thrust chambers.

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Space Propulsion Technology

Work Progresses on High-Performance Onboard Spacecraft Propulsion

NASA Lewis has been working with the Aerojet Propulsion Division of GenCorp since 1985 to develop high-temperature, oxidation-resistant thrusters for spacecraft applications. The successful development of this technology will provide higher performance thrusters that have reduced plume contamination and use conventional storable propellants. Alternatively, this technology program will provide a material that operates at conventional temperatures and increases the life of refuelable or reusable spacecraft.

The new chamber material consists of a rhenium substrate coated with iridium for oxidation protection. Attitude control engines fabricated from iridium-coated rhenium have demonstrated steady-state specific impulses 20 to 25 lbf-sec/lbm higher than those delivered by state-of-the-art silicide-coated niobium chambers, and apogee/orbit transfer engines are expected to deliver an additional 10 to 15 lbf-sec/lbm. Higher performance attitude control engines can extend the life of an Intelsat 7 satellite by an estimated 3 years. Higher performance orbit transfer engines could increase the scientific payload of a CRAF/Cassini mission by an estimated 600 kg. Alternatively, using this new material for the space shuttle orbiter vernier engines extends the life of these engines from 10 missions to an estimated 50 missions and has been accepted for the Assured Shuttle Availability Program.

The performance of these small chemical rockets has been limited by their maximum operating temperature, which is maintained by the use of fuel film coolant. The coolant level reaches 30 to 40 percent of the total fuel for small thrusters and severely penalizes their performance. The state-of-the-art materials for these thrusters are silicide-based protective coatings on a niobium substrate.

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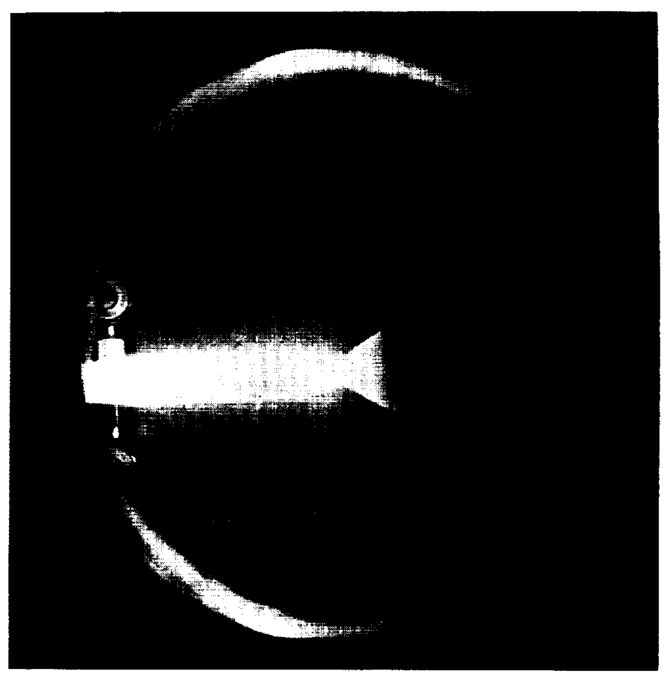

Flight type of 5-lbf space shuttle orbiter vernier thruster.

Their upper temperature limit is approximately 1400 °C. Because of the difference in thermal expansion between the materials, repeated temperature cycling cracks the coating and ultimately destroys the base material. A new high-temperature material system consisting of an iridium coating on a rhenium substrate permits the removal of all fuel film cooling and its associated performance losses without compromising the pulsing duty cycle when appropriate combustion chamber design measures are taken. This material system operates at approximately 2200 °C—an 800 deg C increase in operating temperature. The coefficients of thermal expansion for these two materials are very closely matched, thereby eliminating all effects of repeated temperature cycling on coating integrity. The life of the thruster is then determined by the iridium oxidation rate and the interdiffusion rates of iridium and rhenium. A life of at least 15 hr has been demonstrated at 2200 °C.

These new materials are formed into the complex geometry of small rocket chambers by a net-shape chemical vapor deposition (CVD) process. Design and fabrication efforts with these new materials are ongoing in the 5-, 15-, and 100-lbf class rockets along with metallurgical joining procedures with stainless steel head-ends. Structural fatigue in the throat region during shuttle launch is a potential problem. Methods to mitigate fatigue include fabricating a nozzle skirt from the relatively lightweight niobium material and metallurgically attaching it to the rhenium chamber.

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Rocket Combustor Interactive Design Methodology Speeds Analysis

An interactive computer methodology for the design and analysis of stable high-performance liquid rocket engines has been developed. The computer methodology, Rocket Combustor Interactive Design (ROCCID), provides a framework with which to link and share the inputs and outputs of existing stability and performance prediction design tools in an efficient and user-friendly fashion. ROCCID contains the logic for interactively creating a combustor design that will meet performance and stability goals. A preliminary design is obtained by the application of historical correlations to the input design requirements. The steady-state performance and combustion stability of this design are evaluated by using the selected analysis tools. ROCCID guides the user as to the design changes required for satisfying the performance and stability goals, including the design of stability aids.

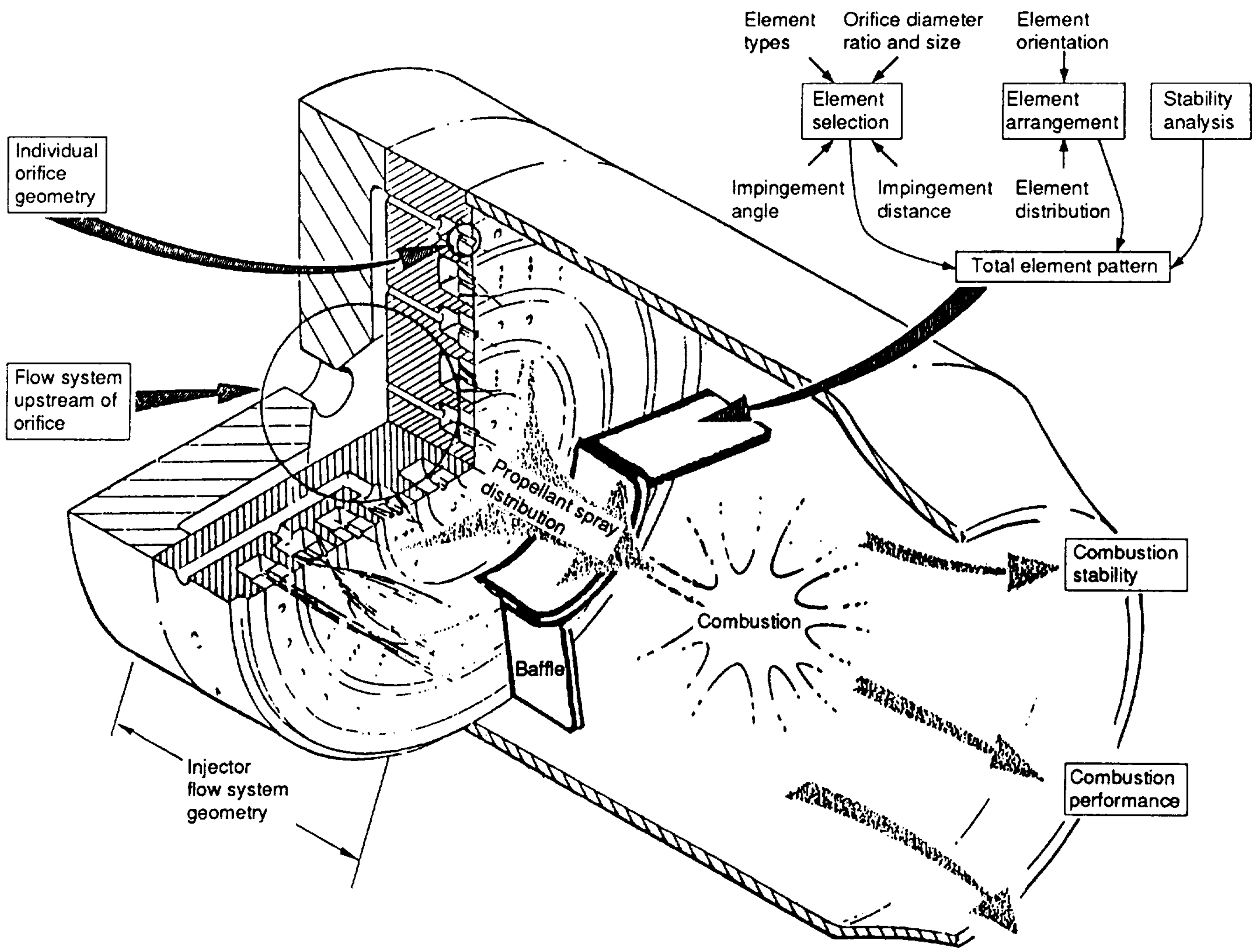
ROCCID is currently capable of analyzing combustors with uniform or mixed injection element patterns containing like doublet or unlike triplet impinging, showerhead, shear coaxial, and hydraulic hollow-cone swirl coaxial elements. Real propellant properties for liquid and gaseous oxygen, hydrogen, methane, and propane and liquid RP-1 are included in ROCCID, and other propellants can easily be added. The modules in ROCCID can account for the influences of acoustic cavities, Helmholtz resonators, and radial chamber baffles on combustion stability. Output from ROCCID includes a formatted input file for the standardized Joint Army-Navy-NASA-Air Force Interagency Propulsion Committee (JANNAF) engine performance procedure.

Users of ROCCID have reported completing analysis tasks 5 to 10 times faster. Recently, an Air Force contract reported that the cost for a task was reduced "... due to efficiencies attributable to the use of the ROCCID computer methodology ..."

Bibliography

Pieper, J.L.; and Muss, J.A.: Development of a Combustor Analytical Design Methodology for Liquid Rocket Engines. 26th JANNAF Combustion Meeting, Vol. 2, D.L. Becker, ed., CPIA-PUBL-529-VOL-2, 1989, pp. 223-232.

Klem, M.D.; Pieper, J.L.; and Walker, R.E.: Combustor Design and Analysis Using the Rocket Combustor Interactive Design (ROCCID) Methodology. AIAA Paper 90-2240, July 1990. (Also NASA TM-103165.)



Analysis of rocket combustor.

Klem, M.D.; and Breisacher, K.J.: A Comparison of Analytical Results for 20 K LOX/Hydrogen Instabilities. AIAA Paper 90-2241, July 1990. (Also NASA TM-103166.)

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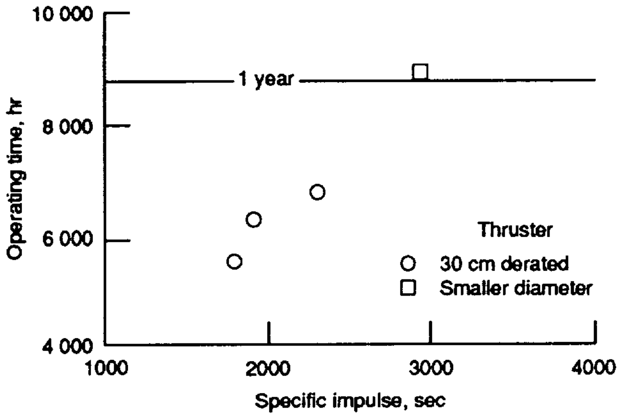
"Derated" Ion Thruster Demonstrated for North/South Stationkeeping Applications

NASA Lewis is evaluating the impact on operations and the risk of using a derated ion thruster for north-south stationkeeping (NSSK) applications on geosynchronous satellites. A derated thruster is defined here as a large (30-cm diameter) ion thruster operated at NSSK power levels, which are typically an order of magnitude below the design point of the thruster. All other proposed near-term NSSK applications of ion propulsion involve the use of relatively small (≤13-cm diameter) ion thrusters operated near both thermal and current density limits. The new derated approach affords significant performance advantages over conventional ion thruster approaches to NSSK, permits the virtual elimination of lifetime as an issue in the first manifestation of ion thrusters, and provides a growth option to primary propulsion applications.

A derated xenon ion thruster has demonstrated a 33:1 power and thrust throttling capability and operates at 620 W for the NSSK application. A specific impulse of 2000 sec was obtained at a 30-MN thrust level. The



Reduced operating time over smaller thrusters.

design of major components, such as ion optics and cathodes, was evolved after many thousands of hours of operation. Efforts to validate 10,000-hr life capability of the thruster assembly are presently under way.

Relative to smaller diameter thrusters, the derated ion thruster concept reduces on-orbit thrusting times by about 70 percent because of a major increase in thrust for a given input power. Lower ion current densities of the derated thruster permit reduced internal and external electrode voltages and thus lower erosion and longer life. Relative to conventional ion thrusters, for example, the internal thruster erosion is reduced by 415 times, external erosion by 30 times, and thruster metal efflux by 38 times.

The derated thruster has a significant growth potential, with a lifetime projected to be greater than 12,000 hr at 5 kW, on the basis of a recent 900-hr wear test at 5 kW. Therefore, the derated thruster approach to NSSK would be of immediate relevance to near-term primary propulsion requirements as well.

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Hydrogen Arcjets Suited for Primary Propulsion

Chemical systems are currently used to perform Earth orbit transfers. Electric propulsion can provide significant mass savings for this function if long transfer times can be

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Hydrogen arcjet test facility.

tolerated. The high-power hydrogen arcjet is well suited to these types of mission and, given the recent acceptance of low-power arcjet tech-nology for auxiliary propulsion on geosyn-chronous communications satellites, may represent the next step in the evolutionary trend toward the use of electric propulsion in space. NASA Lewis has begun an R&T program aimed at developing hydrogen arcjets for primary propulsion functions.

In an arcjet thruster the propellant is heated by an arc and exhausted at an average velocity above that attainable with chemical rockets. Resultant mass savings can be used to improve payload capabilities, to increase satellite lifetime, or to reduce launch mass.

To date, the Lewis program has focused on obtaining realistic performance envelopes for these types of device. For this, a dedicated test facility has been constructed in a large vacuum chamber to provide precision thrust and mass flow measurements along with intrusive plume diagnostics for use in impact assessments. A parametric evaluation of critical component geometries has been performed, and test results have shown that specific impulses of 1000 to 1400 sec are obtainable. Throttleability over a wide power range has also been demonstrated. The next major goal will be a life assessment; a facility for this is now under consideration.

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Tubular Copper Thrust Chamber Design and Fabrication Studied

A dual-phase, focused-technology study was begun as part of the Chemical Transfer Propulsion Program. This study involved the design and analysis of a tubular thrust chamber for an expander-cycle engine that would have improved heat transfer and would incorporate advanced fabrication methods for longer life, lower cost, and reduced weight.

The first phase was a contract effort (Pratt & Whitney) that had two subtasks. Subtask I was to determine an optimum design for tubular cooling passages with high thermal performance. It also included a determination of the thrust chamber life at the design point. Subtask II was a final design of a full-size, contoured thrust chamber to be tested in the advanced expander-cycle test bed (AETB).

The second phase was based on the preliminary analysis of subtask I. This showed that heat transfer can be improved by using a high-conductivity, copper, tubular thrust chamber. In order to take advantage of this configuration, electroforming was investigated as an advanced method of fabrication.

On the basis of a parametric study of engine cycles for a 7500- to 50,000-lb-thrust engine, a thermal analysis of tubular thrust chambers was recommended. This analysis was required in order to optimize an expander-cycle engine with a tubular thrust chamber.

The thermal analysis showed that the tubular thrust chamber configuration promised a 18- to 40-percent additional enthalpy extraction with a coolant pressure drop approximately the same as a state-of-the-art (space shuttle main engine) channel chamber configuration.

After completion of the analysis, scaled test chambers were fabricated for the proof of concept of the electroforming fabrication technique as well as of thermal performance and cyclic life. These chambers passed hydrostatic pressure testing at twice the design pressure without failures or leaks. They also incorporated improved fabrication and metallurgical bonding of the tubes without the use of thermal processing, such as welding or brazing. These chambers also included the first attachment of manifolds without welding.

After the scaled testing and the final contoured chamber preliminary design have been completed, the decision will be made about fabrication of a contoured chamber for testing in the AETB.

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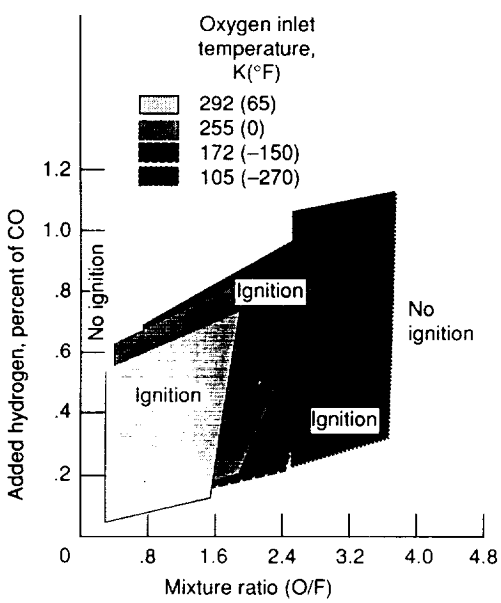
Engine Performance With Carbon Monoxide and Oxygen Propellants Investigated

The NASA Space Exploration Initiative calls for the exploration and eventual settlement of the solar system. The production of propellants from the resources available at the Moon and Mars has been shown to offer significant mission benefits including lower launch costs, shorter trip times to Mars, larger payload capability, and reduced mission complexity. The atmosphere of Mars is almost entirely carbon dioxide, which can be broken down into carbon monoxide (CO) and oxygen (O_2) and used as propellants for Mars launch and for the return trip to Earth. Most Earth-based engines use hydrogen or hydrogen-bearing fuels, but there is little or no hydrogen on Mars. Carbon monoxide fuel has never been tested in a rocket engine.

NASA Lewis has begun a technology program to investigate the performance potential of carbon monoxide and oxygen propellants combusted in a rocket engine. The objectives of the program are to quantify the ignition characteristics, to measure performance efficiencies, and to determine heat transfer characteristics of the combustion gases.

Ignition tests were completed in June 1990. Because of the slow kinetic reaction rate of CO and O_2, successful ignition occurred only when small amounts of hydrogen (approximately 0.05 percent) were added to the fuel stream. This hydrogen acted as a catalyst to begin the reaction. Once ignition was achieved, combustion was sustained without hydrogen addition. Successful ignition was also dependent on mixture ratio and inlet gas temperature.



CO/O_2 ignition profiles for various oxygen and inlet temperatures.

Subscale combustion tests in heat sink hardware were completed in December 1990. An eight-element fuel-oxide-fuel triplet injector was used. Preliminary data analysis indicates that a concentric tube injector design could improve the 90-percent C^* efficiencies that were obtained with the triplet injector. Additionally, calorimeter engine tests could identify areas of high heat loss to the walls that may have reduced efficiency.

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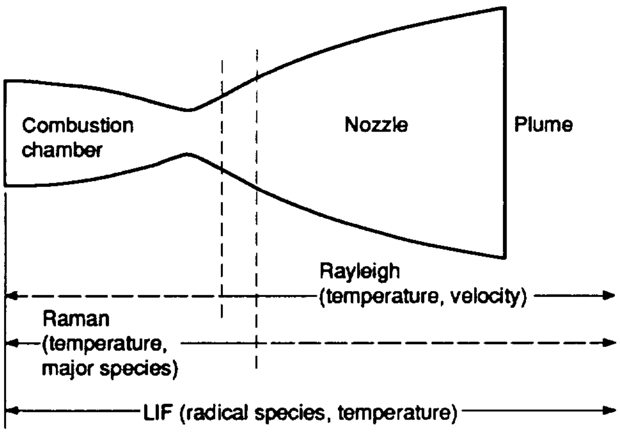
Laser Diagnostic Measurements Being Made in Chemical Rockets

Measured performances for low-thrust chemical rockets consistently fall significantly below those predicted by currently used state-of-the-art models, although the reasons for these discrepancies are not clear. Nonintrusive laser diagnostic measurement techniques are being developed to investigate combustion and gas dynamic phenomena occurring in small chemical thrusters and to support the development of new predictive technologies. Since one measurement technique is not capable of measuring all parameters of interest in all regions of the thruster, a battery of complementary diagnostics is being pursued. These include laser Rayleigh scattering, laser Raman scattering, and laser-induced fluorescence (LIF). The gas properties measured and the general regions of applicability of these techniques are shown in the figure.

Rayleigh scattering is essentially the elastic scattering of light by gas molecules. Through high-resolution spectral analysis of the Rayleigh scattered spectrum, velocity,



Laser diagnostic applications to chemical rockets.

temperature, and number density estimates can be obtained. Initial Rayleigh scattering measurements in the exit plane/plume region of a 25-lbf-thrust gaseous hydrogen/oxygen thruster (30:1 area ratio) operating in a high-altitude test facility (0.2 psia) have been successful (ref. 1). Modifications are currently under way to quantify both axial and radial velocity components and to utilize a high-power Nd:YAG pulsed laser system.

Raman scattering, or inelastic molecular light scattering, is limited to regions of higher number density because of its inherently weak signal strength. Its value, however, is that the number densities and temperatures for all major species can be measured simultaneously. A fiber-optic-based Raman scattering system utilizing a high-pulse-energy flashlamp-pumped dye laser (2 joules/pulse) is being applied in the exit plane of a low-area-ratio (1.4:1) thrust chamber (ref. 2). The Raman system will be applied to the investigation of processes occurring in fuel-film-cooled combustion chambers by using an optically accessible two-dimensional rocket.

Laser-induced fluorescence, or resonance absorption followed by emission, is being developed in conjunction with the Raman system. LIF is applicable to the detection of important radical species such as OH. The inherently strong LIF signal allows instantaneous measurements of OH to be made over an entire two-dimensional flow field, thus allowing the reaction zone to be spatially characterized.

References

1. Seasholtz, R.G.; Zupanc, F.J.; and Schneider, S.J.: Spectrally Resolved Rayleigh Scattering Diagnostic for Hydrogen-Oxygen Plume Studies. AIAA Paper 91-0462, Jan. 1991.

2. DeGroot, W.A.: Fiberoptic-Based Raman Scattering for Species and Temperature Measurement in H_2/O_2 Rocket Flows. To be presented at the 27th Joint Propulsion Conference, June 26, 1991, Sacramento, CA.

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Heat Transfer of Tubular Rocket Thrust Chambers Analyzed

In the design, evaluation, and optimal performance of advanced high-pressure rocket engines, knowledge of the heat transfer rates from the exhaust gases to the coolant is critical. Heat transfer considerations are especially important in expander-cycle rocket engines, where the heat exchanged from the rocket engine exhaust gases to the coolant fluid is used for the operation of turbopump assemblies.

The emergence of rocket engines constructed of tubular coolant chambers has made the determination of heat transfer characteristics substantially more difficult. The reason is the corrugated surface created in bundling the tubes together to create a rocket engine. Exposing this corrugated surface to hot rocket engine exhaust gases results in peripheral variations in heat transfer rates.

An advanced analysis of a tube-bundle rocket engine was performed to explore the likely extent of circumferential heat transfer variation. A three-dimensional, second-order-accurate, Navier-Stokes code, PARC3D, was used to evaluate the corrugated wall structure. For comparative purposes a smooth-wall configuration was also analyzed.

Predictions at the rocket nozzle throat indicate that heat fluxes will decrease modestly (about 20 percent) in the region near the tube crevice. However, when combined with the greater surface area of the tube-bundle engine (relative to a smooth-wall engine), the significance of the corrugated geometry is apparent. Overall (i.e., integrated) heat transfer rates are predicted to be 34 percent greater with the tube-bundle engine. Therefore, tube-bundle rocket engines offer a means of increasing overall heat transfer without the need to increase heat flux rates or reduce wall temperatures—options that are undesirable as they reduce rocket engine performance.

Experimental verification is required, including investigation of the effect of chamber pressure (hence Reynolds number) and the sensitivity of the tube-bundle design to heat transfer.

Bibliography

Kacynski, K.J.: A Three-Dimensional Turbulent Heat Transfer Analysis for Advanced Tubular Rocket Thrust Chambers. NASA TM-103293, 1990.

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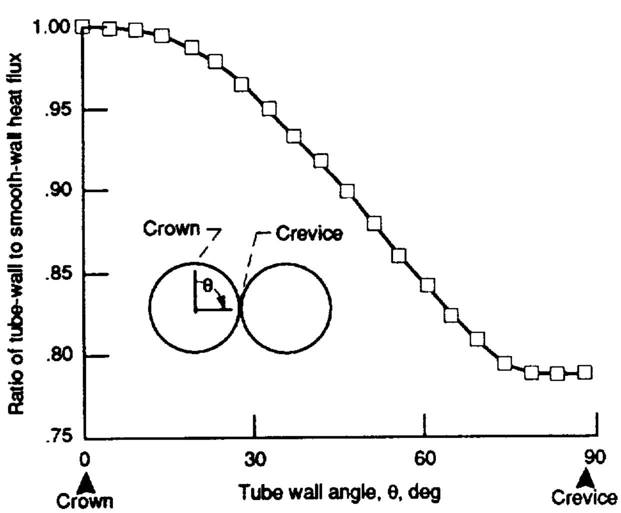
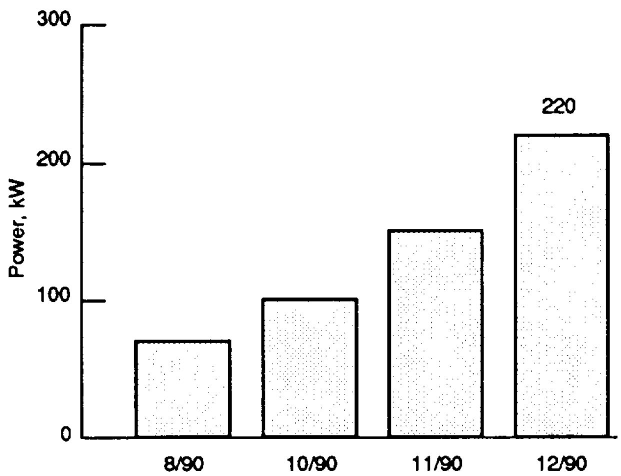


Turbulent heat transfer suppression in tubular rocket engines.

Magnetoplasmadynamic Thruster Shows Fourfold Power Increase

Magnetoplasmadynamic (MPD) thrusters use a high-current electric arc to generate electromagnetic body forces that accelerate propellants to exhaust velocities greater than 30 km/sec. Mission studies for the Space Exploration Initiative show substantial launch cost reductions from using this propulsion technology. Thruster power levels above 1 MW will be required to accomplish the missions in the desired trip times. Prior testing has typically focused on power levels below 50 kW, which limit thrust levels to less than 0.5 N. To explore the operating range of MPD thrusters, NASA Lewis has designed and implemented a high-power test stand in a large (25- by 80-ft) vacuum facility. Up to 390 kW is available for thruster testing. Performance is directly measured with a novel thrust stand over 5 ft high along with associated power and propellant flowmeters. The high-speed pumping capability allows thruster operation at pressures of less than 10^{-7} atmospheres. Testing has included several thruster electrode configurations with water-cooled anodes from 5.1 to 10.2 cm in diameter, solid cathodes from 1.3 to 2.5 cm in diameter, and hollow cathodes with low-work-function inserts. Large-bore solenoids are used to generate magnetic fields ranging from 0.02 to 0.4 tesla in the interelectrode region. A suite of diagnostics is used to measure electrode power deposition and surface temperature, electrode life, and rocket plume characteristics.

Significant progress has been made in recent tests. A fourfold increase in thruster operating power to over 200 kW was demonstrated with a 10.2-cm-diameter anode. Thrusters have been tested with hydrogen and argon propellants at arc currents up to 2500 A. The maximum demonstrated thrust and specific impulse were 2.3 N and 3700 sec, respectively. The applied solenoidal magnetic field dramatically improved thruster performance: A factor-of-3 increase in power-to-thrust conversion efficiency and specific impulse was observed when the applied magnetic field was increased over the available range. Measurements of the rocket plume density and temperature distributions have been made by using single and triple Langmuir probes mounted on a high-speed actuator. Hall effect



Demonstrated MPD thruster power.

transducers have been used to measure the arc current distribution. Noninvasive spectroscopic and imaging techniques are used to measure plume species distributions.

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Low-Power-Arcjet Integration Demonstrated

Over the past 7 years, a significant effort at NASA Lewis has focused on the development of low-power arcjet thrusters for use in north-south stationkeeping of geosynchronous communications satellites. Under this effort, mission-average specific impulse levels above 450 sec have been demonstrated—a factor-of-1.5 improvement over state-of-the-art technology. Flight type of system components have been developed and have successfully passed both environmental qualification and life requirements. A final, major hurdle to acceptance in the user community was the demonstration of arcjet system/spacecraft compatibility. A major contracted effort was undertaken in this area.

In the Arcjet System Integration Demonstration (ASID) a 1.4-kW, flight type of arcjet system developed under a NASA contract at the Rocket Research Company was tested with the Fltsatcom qualification model satellite at TRW, Inc. The testing was carried out in a 30-ft-diameter space simulation chamber in two test sequences. In the first the arcjet system and diagnostics were tested at a relatively high background pressure in order to check out all system elements. This was

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Arcjet and Fltsatcom qualification model spacecraft in space simulation chamber.

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followed by high-fidelity testing at a background pressure of approximately 1×10^{-5} torr. Power for the arcjet was supplied by the Fltsatcom battery, and operational spacecraft subsystems were monitored throughout the tests. Conducted and radiative electromagnetic interfaces (EMI) were measured as were radiative and convective heat transfer.

The testing was successfully completed in July 1990; no major impediments to commercial satellite applications were found. Telemetry showed that spacecraft subsystem operation was unaffected by steady-state or transient arcjet system operation. No measurable EMI signals were observed in typical communications satellite command or communications bands. Some broadband noise above military specification limits was observed below 40 MHz. The source of this noise is not presently understood and is under investigation. Radiative and convective heat flux measurements were also obtained for generic use in integration analyses.

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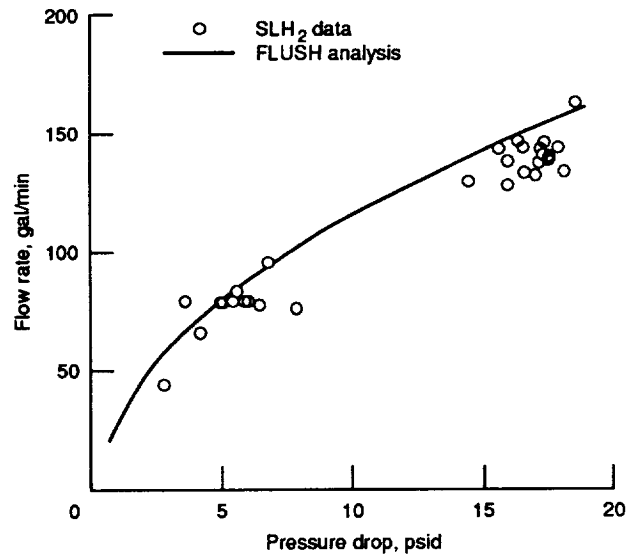
Slush Hydrogen Propellant Transfer and Tank Propellant Studies Performed

Slush hydrogen (SLH_2), a mixture of solid and liquid hydrogen, is currently being considered for use as a fuel in the National Aerospace Plane (NASP) Program. The slush hydrogen provides the potential advantages of higher fuel density and greater heat capacity relative to normal-boiling-point liquid hydrogen. These advantages have been quantified as being between 13 and 26 percent savings in gross takeoff weight for NASP (ref. 1). However, before slush hydrogen can be used as a fuel on NASP, several technology issues must be examined. These issues include slush hydrogen production techniques, fuel tank pressure control methods, and transfer of large quantities of slush hydrogen through piping systems. Therefore, an experimental program is being conducted at NASA Lewis to address these issues.



Comparison of experimental flow data with FLUSH analysis.

Production, transfer, and tank expulsion tests have been performed at the NASA Plum Brook K-Site Facility located in Sandusky, Ohio. In these tests slush hydrogen was produced in a 1300-gal slush hydrogen generator by the evaporative cooling, or freeze-thaw, technique. In most cases the slush hydrogen had a solid fraction of 50 percent or greater at the end of production. Following production the slush hydrogen was transferred through a cryogenic flow system approximately 125 ft long to a 5-ft-diameter spherical test tank, located inside a 25-ft-diameter vacuum chamber. Once the test tank had been filled with slush hydrogen, the tank was pressurized with gaseous hydrogen, and the fluid was transferred back to the slush generator by a pressurized expulsion technique.

Output from the transfer tests included flow-rate-versus-pressure-drop characteristics as well as solid fraction loss during the transfer. These experimental results were compared with results from the NASA Lewis FLUSH code. FLUSH is a one-dimensional model developed under the NASP program for predicting drop and solid fraction loss for slush hydrogen transfer through flow systems (ref. 2). The FLUSH code predicted the flow characteristics of slush hydrogen well.

Expulsion tests were performed by varying the tank pressure, the slush hydrogen outflow rate, and the pressurant gas temperature. Output from the expulsion tests included the thermodynamic parameters required for analyzing tank pressure control of the NASP vehicle: pressurant gas requirements for a constant-pressure expulsion, temperature profiles in the tank ullage and the tank wall, and slush hydrogen density. Initial tests performed at the K-Site Facility used gaseous hydrogen as the pressurant gas. Future tests will use gaseous helium and mixtures of helium and hydrogen to control tank pressure during expulsion.

References

1. DeWitt, R.L., et al.: Background, Current Status, and Prognosis of the On-going Slush Hydrogen Technology Development Program for the NASP. NASA TM-103220, 1990.

2. Hardy, T.L.: FLUSH: A Tool for the Design of Slush Hydrogen Flow Systems. NASA TM-102467, 1990.

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Preliminary Design of Advanced Expander-Cycle Test-Bed Engine Completed

As part of the Exploration Technology Program, the Space-Based Engine Program has the objective of providing the technology base necessary to confidently begin the development of an advanced space engine. The advanced expander-cycle test-bed (AETB) engine is used to help meet that objective.

Technologies, subcomponents, and components for an advanced space engine have been investigated for several years. The AETB represents the initial effort to integrate the results of those investigations into a test-bed engine in order to investigate system issues, such as component interactions, system transients, system dynamics, control schemes, and engine health management systems. The AETB will also serve as a test bed to evaluate advanced-technology, mission-focused components as they become available from other space-based engine contracts.

The AETB contract (NAS3-25960) was awarded to Pratt & Whitney of West Palm Beach, Florida, in April 1990. The test-bed engine preliminary design was completed in 1990, and a preliminary design review was presented to NASA in January 1991. Engine characteristics include

(1) Propellants, liquid hydrogen and liquid oxygen
(2) Engine cycles, split expander and full expander
(3) Design point, thrust (125 percent) of 25,000 lbf and chamber pressure of 1500 psia
(4) Normal operating point, thrust (100 percent) of 20,000 lbf and chamber pressure of 1200 psia
(5) Throttling, 125-percent thrust to 5-percent thrust (continuous and stable)
(6) Idle modes, pumped (zero net positive suction pressure) and tankhead (nonrotating)
(7) Mixture ratio, 6.0±1.0 and 12.0
(8) Life, 100 starts in 5 hr before overhaul

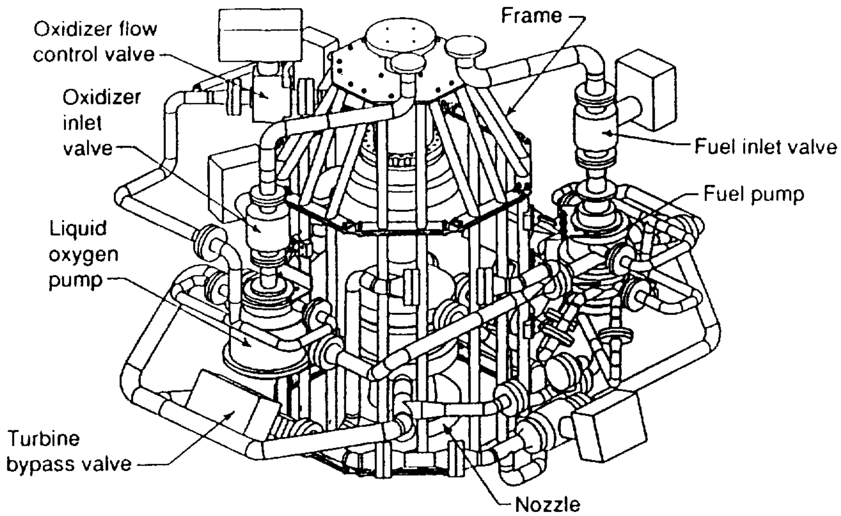
Engine features include

(1) Fuel pump:
- (a) Twin, back-to-back, counterrotating shafts with subcritical rotordynamics
- (b) Rolling-element bearings
- (c) Full-admission reaction turbines
- (d) Dual, vaneless volute diffusers

(2) Oxidizer pump:
- (a) Knife-edge, labyrinth interpropellant seal
- (b) Single-stage, full-admission reaction turbine
- (c) Rolling-element and ball bearings

(3) Thrust chamber, milled-copper construction
(4) Exhaust nozzle, sea-level-test, tubular-construction nozzle (area ratio, 7.5)
(5) Controller:
- (a) Brassboard based on NASP design
- (b) Modular architecture
- (c) Flexible and versatile

The preliminary design has been approved and the final design has been started. The contract requires delivery of two identical test-bed engines to NASA Lewis and assistance for testing the test-bed engine at NASA. Also contractually required are (1) a steady-state and a transient computer model of the test-bed engine and (2) verification tests for various



Advanced expander-cycle test-bed engine.

computer codes used in the design and analysis of the test-bed engine.

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Metallized Propellants Show Promise for Mars Missions

In the Metallized Propellant Program the technologies for using metal additives in gelled liquid fuels are being developed. These additives increase the engine specific impulse, or the propellant density, or both. Increasing either of these can, in turn, increase a space vehicle's payload. Propellant handling is also safer with gelled propellants. Fuel spills are smaller with gelled liquids, and the propellant is less likely to combust during an accidental release. Typically, aluminum particles are suspended in gelled fuels—hydrogen, RP-1, or monomethyl hydrazine. Ongoing research will quantify vehicle and engine performance, propellant chemistry, and production.

Over the last year a series of vehicle system analyses and experimental programs were conducted to identify the best applications for metallized propellants and to demonstrate the technologies of propellant formulation.

Piloted missions to Mars and the Moon can derive several benefits from using metallized propellants. Using metallized oxygen/hydrogen/aluminum ($O_2/H_2/Al$) for a piloted Mars mission can deliver 20 to 33 percent additional payload to the surface (ref. 1). Propellants such as nitrogen tetroxide/monomethyl hydrazine/aluminum (NTO/MMH/Al) and O_2/MMH/Al can provide Earth- and space-storable options for a Mars ascent stage of a manned Mars mission. The higher boiling point of these propellants minimizes or eliminates propellant boiloff losses. The added payload delivered to Mars with these propellants relative to O_2/H_2 is only 3 to 5 percent of the initial mass of the vehicle in low Earth orbit (ref. 1). On lunar cargo missions the added payload delivered is a modest 2 to 3 percent (ref. 2). This option does not demonstrate a large gain for metallized propellants, but the lunar mission might be used as a test bed for future, more ambitious Mars missions.

For upper stages propelling robotic planetary missions, metallized $O_2/H_2/Al$ and NTO/MMH/Al have very significant potential, especially for high-energy fast planetary missions (ref. 3). On an outer planet flyby metallized propellants used in an upper stage (launched with a heavy-lift launch vehicle) can deliver 28 percent more injected mass onto a planetary trajectory (with an injection energy C_3 of 150 km^2/sec^2). For a Jupiter orbiter mission an upper stage using NTO/MMH/Al can deliver 97 percent more injected mass than NTO/MMH (at a C_3 of 80 km^2/sec^2).

Cryogenic gellants for metallized fuels are being formulated and demonstrated at TRW, Inc. Very low-temperature fuels such as propane, methane, and hydrogen may be important for future NASA launch vehicle and space transfer systems. Using silica-based gellants, hexane and propane have been gelled with and without added aluminum. These gellants are a major step toward making gelled cryogenic fuels practical. Past gels had required 10 to 30 percent of the fuel to be a gellant. The new gellants are less than 1 percent of the total amount of the fuel. The ultimate goal of this research is to produce gelled hydrogen/aluminum fuel that is 60 percent aluminum.

References

1. Palaszewski, B.: Metallized Propellants for the Human Exploration of Mars. NASA TP-3062, 1990.

2. Palaszewski, B.: Lunar Missions Using Advanced Chemical Propulsion: System Design Issues. AIAA Paper 90-2431, July 1990. (NASA TP-3065, to be published.)

3. Palaszewski, B.: Advanced Launch Vehicle Upper Stages Using Liquid Propulsion and Metallized Propellants. NASA TM-103622, 1990.

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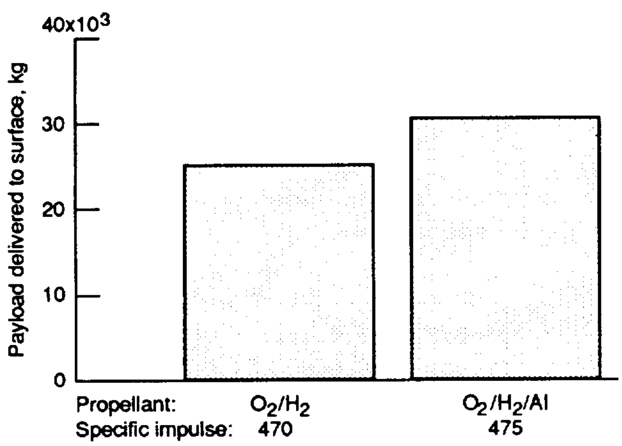
Headquarters program office: OAET



Metallized propellants for piloted Mars missions.

High-Energy-Density Propellants Studied

Ongoing theoretical and experimental work in the Advanced Concepts Program is directed toward basic research on methods of using atomic hydrogen and other highly energetic materials for launch vehicle and upper stage propulsion.

A possible method of increasing the performance of chemical rocket engines is using higher energy propellants. Some of the most energetic chemical compounds and atoms, however, are unstable and have very short life. Atomic hydrogen is an example of this type of atom. Upon recombining, atomic hydrogen atoms release tremendous energy. Studies of this atom as a potential propellant have shown great promise for rocket propulsion. A specific impulse of one and one-half to four times that of the highest-performing chemical propellants may be attainable (ref. 1). Efficiently creating, storing, and using these atoms, however, is not easy. This program seeks ways to control these atoms for useful rocket propulsion.

In 1990, research continued at two universities and work was begun with the Department of Energy. In-house studies of the rocket engines and propellant storage systems are also continuing at NASA Lewis.

The University of Iowa has completed a study of the specific impulse and energy density of over 30 high-energy-density materials. An important result of this survey was the realization that many potential propellant materials exist with specific impulse potential between 500 and 600 lbf-sec/lbm. Several newly conceived chemical reactions may produce performance levels near 1000 lbf-sec/lbm.

Experiments to determine the storage density of atomic hydrogen are under way at the University of Hawaii. The experiments include measurements of the thermal and optical energy release during atomic hydrogen recombination. Computer modeling of atomic hydrogen in a solid molecular hydrogen storage medium is also under way. Experimental results show a marked difference between the density predicted with two

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different measurements. These discrepant estimates are under investigation.

The use of powerful magnets has been proposed by Oak Ridge National Laboratory for the long-term storage of atomic hydrogen and other free-radical propellants.

References

1. Palaszewski, B.: Atomic Hydrogen as a Launch Vehicle Propellant. AIAA Paper 90-0715, Jan. 1990. (Also NASA TM-102459.)

Lewis contact: Bryan Palaszewski, (216) 433-2439
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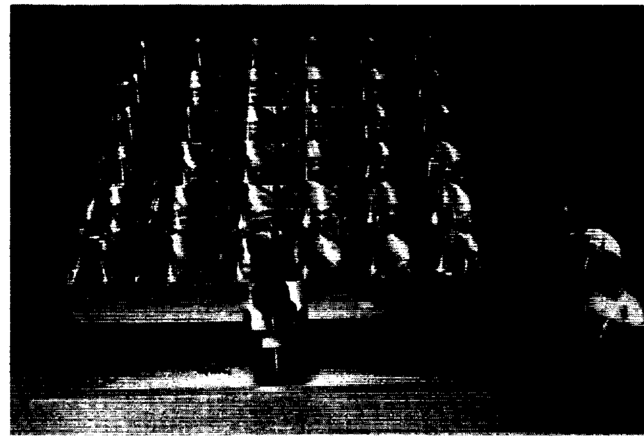

Mini-dome Fresnel lens photovoltaic concentrator: 36-element prototype panel.

Power Technology

Mini-Dome Fresnel Lens Demonstrated for Photovoltaic Concentrator Array

Photovoltaic concentrator arrays for space power systems offer the advantage of operating smaller photovoltaic devices at higher efficiencies. However, losses encountered in collecting and concentrating the sunlight can diminish the gains of higher operating cell efficiency and make increases in system performance marginal. The mini-dome Fresnel lens concentrator is a high-efficiency, lightweight concept that greatly enhances the inherent advantages of space photovoltaic concentrator systems.

The mini-dome Fresnel lens concentrator is a point-focus refractive lens that was developed under a Small Business Innovative Research (SBIR) contract by Entech, Inc., of Dallas, Texas. The concentrator lens has a smooth outer surface with individually tailored Fresnel facets along the inside of the domed surface. The combination of the domed shape and the Fresnel facets provides a unique geometry that minimizes reflection from each Fresnel prism, thereby providing maximal sunlight transmittance through the lens. Under the current design the concentrator unit is made from a flexible silicone that can then be bonded to a supporting superstrate to add stiffness to the structure. Each lens provides a concentration of 100 suns to a high-efficiency photovoltaic concentrator cell at a focal length of 4.0 cm. In order to increase the packing factor of these devices within an array, each lens is cut to a 3.7-cm by 3.7-cm square aperture. Analytical studies have predicted over 95-percent optical efficiency for a lens with an antireflection coating.

During the past year a number of significant accomplishments have been made. Early in 1990, uncoated prototype concentrator lenses were flown on the NASA Lewis Learjet High-Altitude Test Facility. The efficiency of these lenses was measured at 90 percent under air-mass-zero (AM0) insolation conditions. Work continued on the development of these early lenses with emphasis on the ability to manufacture and consistently reproduce the lens while maintaining high optical performance. A number of high-quality lenses have been made using both glass and polycarbonate superstrates. Other methods of producing high-quality, low-cost lenses that are survivable within the natural space environment are also being pursued.

The major accomplishment of 1990 was the delivery of a 36-element (6 by 6) prototype panel. The panel demonstrates the integration of a number of high-efficiency photovoltaic concepts. It includes six strings of six series-connected gallium arsenide (GaAs) concentrator cells. A prismatic cell cover, which eliminates reflection losses from the top grid lines by refracting the light to the exposed areas of the cell, is applied to the top of each cell to further improve its efficiency. The concentrator lenses are bonded into a square honeycomb structure, improving the packing factor of the array. The panel structure, designed by Entech in conjunction with Boeing Aerospace, demonstrates the feasibility of manufacturing a lightweight array structure that is easily adaptable to current manufacturing processes. The prototype panel, tested under terrestrial conditions, achieved efficiencies of approximately 21 percent, consistent with the expected performance of the components and cells used.

Under an existing Strategic Defense Initiative Office SBIR contract with Entech, work continues on a lightweight version of the mini-dome Fresnel lens concept developed under the NASA SBIR program. Boeing Aerospace is also working on using this array concept in conjunction with a new high-efficiency photovoltaic device. A gallium arsenide/gallium antimonide (GaAs/GaSb) tandem cell structure, developed at the Boeing High Technology Center, has demonstrated a device efficiency of over 30 percent and would nicely fit into the mini-dome Fresnel lens concept. An array using this new cell could have an operating AMO array performance of over 300 W/m^2.

The mini-dome Fresnel lens photovoltaic concentrator concept has the potential to significantly impact future space power systems. Its distinction of integrating high-efficiency components into a relatively lightweight structure makes it suitable for a wide variety of both civil and military space missions.

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Validation Testing Performed on 26 Percent KOH Nickel-Hydrogen Cells

A breakthrough was achieved in the low-Earth-orbit (LEO) cycle life of individual pressure vessel (IPV) nickel-hydrogen battery cells. The cycle life was improved by more than a factor of 10 over state-of-the-art cells. Boilerplate cells containing 26 percent potassium hydroxide (KOH) electrolyte were cycled for 40,000 stressful accelerated LEO cycles at a deep depth of discharge (80 percent). Cells containing 31 percent KOH had achieved only 3500 cycles. The test was conducted at Hughes under a NASA Lewis contract. For long-term LEO missions, such as Space Station *Freedom*, the extension of battery cycle life would result in a significant reduction in life-cycle cost. In addition, operating at a deep depth of discharge would reduce battery mass and increase payload capability.

The boilerplate cell accelerated test results are in the process of being validated by using flight cells and real-time tests. Six Hughes 48-Ahr-capacity IPV nickel-hydrogen flight cells are undergoing cycle life testing under a LEO cycle regime at 80 percent depth of discharge and 10 °C at the Naval Weapons Support Center in Crane, Indiana. Three of

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IPV nickel-hydrogen battery cell.

the cells contain 26 percent KOH (test cells) and three contain 31 percent KOH (control cells).

The cells containing 26 percent KOH have not failed after 13,000 cycles in the continuing test. All three cells containing 31 percent KOH have failed (at cycles 3729, 4165, and 11,355).

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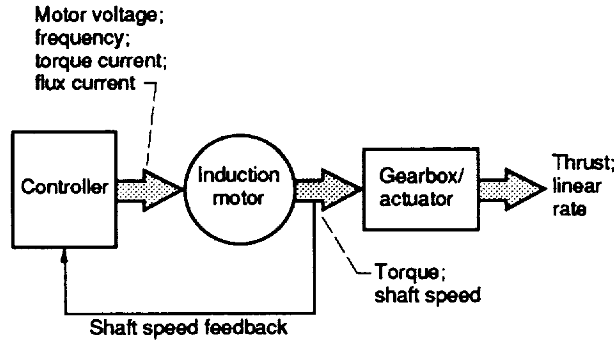

Field-oriented control for induction motors.

Getting More out of AC Motors for Thrust Vector Control of Launch Vehicles

Intelligent electrical actuators developed by NASA Lewis and General Dynamics will steer future launch vehicles into orbit on time and more economically. By merging several technologies, Lewis engineers have demonstrated an electric induction, servomotor-driven, electromechanical actuation (EMA) system to control the thrust direction of large rocket engines. The new actuators will eliminate costly manpower-intensive processing of flows and will enable self-checkout, rapid repair, and launch from late hold.

The electrical actuation tasks are selected key technologies of the Advanced Launch System. The Advanced Launch System is a joint effort by the U.S. Air Force and NASA to demonstrate a pathway to a low-cost, heavy-lift vehicle for propelling cargo into space. Lewis and General Dynamics have demonstrated 5- and 25-hp motor drives and controls, respectively. The 25-hp driver with a mechanical actuator and a nearly completed 40-hp electrical actuator will be fully tested and evaluated as part of an EMA/Power Bridging Program to demonstrate technology readiness for the National Space Transportation System, which will include several new vehicles that are now in the planning stages. Five- to 10-hp EMA's could steer future Atlas- and Titan-class vehicles and control their fuel flows.

The key to the Lewis approach is the use of a universal-design pulse population modulation (PPM) motor drive with field-oriented control by a very versatile digital signal processor (DSP). The controller, coupled with a high-frequency resonant link, switches at zero-crossing and sorts sine pulses of energy into the motor. This process is much gentler on the semiconductor switches and conserves energy. The result is rugged four-quadrant servocontrol of the workhorse induction machine with a small, lightweight, efficient electrical control network. Not only is the power electronics package smaller, but so are the controls and the required energy source. The motor runs quieter—both electrically and acoustically.

Since the intelligence has been built in up front and down into the main elements of the system, the entire system can be monitored for status and health at various stages of assembly and operation. Remote checkout on the launch pad or in flight will also be possible.

The adaptive DSP control will enable parameter tuning of the system to meet changing mission and application demands. For example, the torque of any type of motor operating at any speed within its rating (including stall) can be instantly changed or reversed. The result is a machine capable of switching from the motoring to the generating mode within a matter of microseconds. Using a bidirectional motor driver will permit power to flow in both directions, into and out of the high-frequency link. This ability to rapidly vary developed torque and energy flow will play a critical role in the development of electrical actuation systems and variable-speed motor drives for use on future aircraft, planetary rovers, various valves and pump drives, and any process requiring variable energy flow.

With the advent of smart drivers, large semiconductor switches, and DSP's, efficient and versatile PPM-driven induction motors with field-oriented control make sense everywhere—from home air-conditioners and washing machines to factory processing, advanced launch systems, and fuel-efficient commercial and military aircraft.

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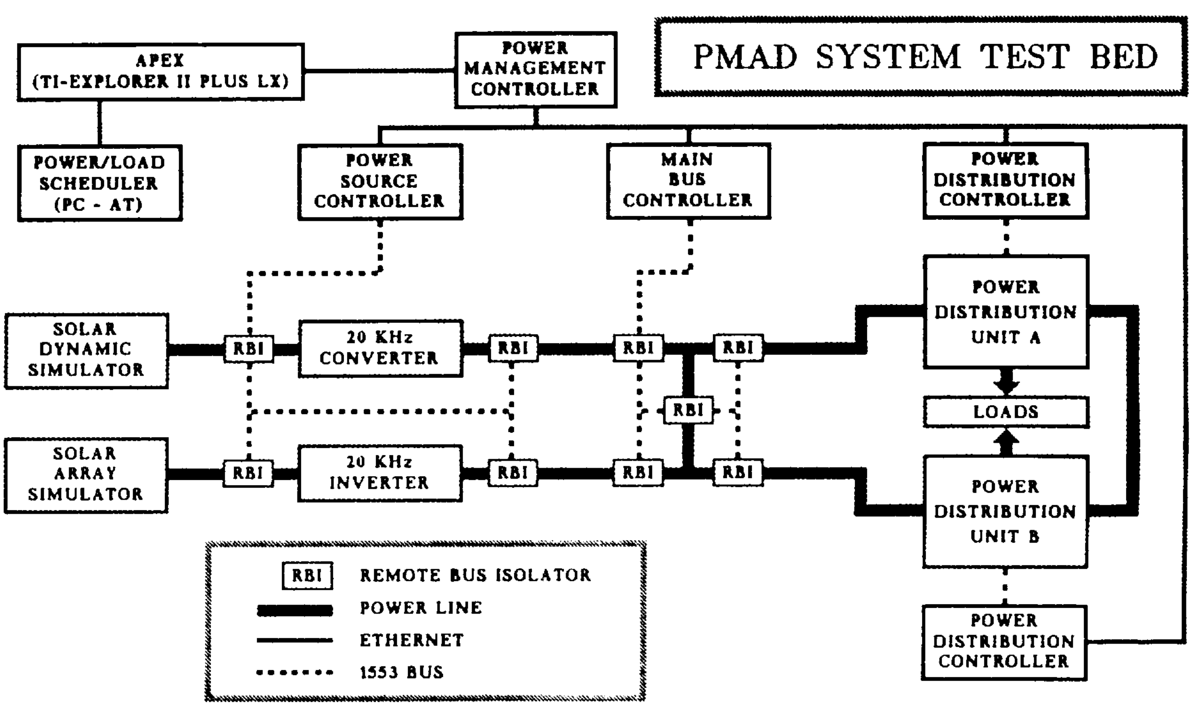
Prototype of Autonomous Power System Developed

NASA Lewis is engaged in an ongoing program to develop and demonstrate knowledge-based system software for the electric power system of Space Station *Freedom* (SSF). Applying artificial intelligence technology to large, complex space power systems will reduce maintenance and operating costs, improve resource utilization, and enhance overall reliability and crew safety. Although traditional automation approaches have been adequate for the preplanned, but complex, mission operations of the space shuttle and unmanned spacecraft, future automation systems clearly must be capable of adapting to uncertain operating conditions and environments and must perform cooperative problem solving both with humans and other intelligent agents.

The Lewis effort has concentrated on the in-house development of a fault-management expert system that can assist system operators in detecting, isolating, and diagnosing power system fault conditions in real time. This intelligent assistant software has been extended to aid in reconfiguring and recovering failed power systems. Lewis has also developed power- and load-scheduling software that enables efficient energy utilization while working in close conjunction with the fault-management expert system.

A prototype version of the automated power expert (APEX) diagnostic expert system has been developed on an artificial intelligence workstation and demonstrated with a small



Autonomous power system.

power distribution brassboard. The system handles a number of different single faults and can detect some multiple faults as well as monitor and detect incipient fault conditions at selected points in the circuitry. A load-scheduling program has also been interfaced with APEX and has been demonstrated to configure and reconfigure electrical load sets of differing time and priority constraints while making maximum use of available energy.

The current effort involves improving APEX to handle more complex fault scenarios and then supporting integration onto a Lewis SSF computer network that will be connected to the control loops for a larger SSF dc test bed now being assembled and tested. Future goals include development of smart electric power control systems with "deeper thought" reasoning that can meet the needs of lunar surface power or planetary exploration.

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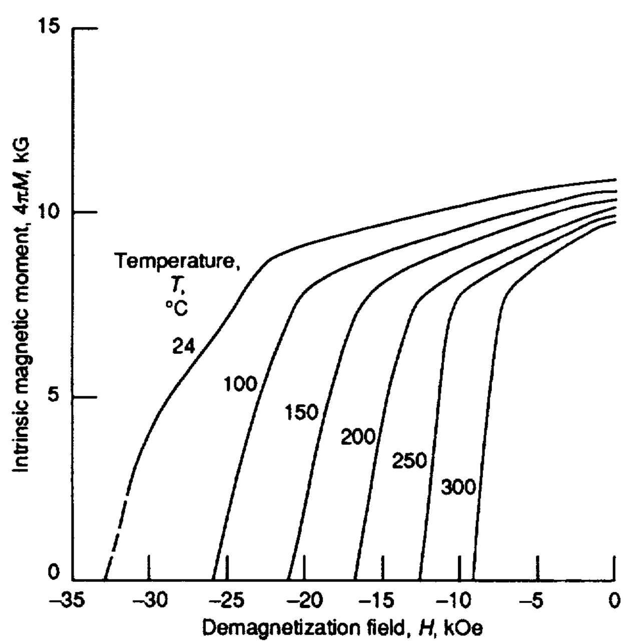
Samarium-Cobalt Permanent Magnets Have Limited High-Temperature Demagnetization Resistance

Temperatures approaching 300 °C are now planned for the exciting magnets to be used in linear alternators coupled to free-piston Stirling engines for multiyear missions in space, where a high heat rejection temperature permits a great reduction in radiator size. At 300 °C the intrinsic coercivity and remanence of even the best rare earth–cobalt magnets degrade rapidly with increasing temperature and perhaps also with passing years. The considerable progress made within the last 10 years in improving the magnetic properties at temperature, particularly of the high-energy Sm_2Co_{17} type of magnet, has depended on finding new heat treatments and alloying additions. Much-needed high-temperature data continue to be scarce because 300 °C measurements are difficult and the complex microstructure of these modern magnets makes extrapolation and prediction of properties unreliable.

NASA Lewis has assembled a basic magnetic measurements laboratory to characterize high-coercivity permanent magnets with respect to short-term demagnetization resistance and long-term aging up to 300 °C. The major instrumentation consists of a capacitor-discharge pulse magnetizer, a 10-in.-pole-size variable gap electromagnet, a temperature control fixture and associated magnet sample holder, and field measurement electronics. We can pulse magnetize 1-cm cubic samples with peak fields of 13 T and measure their demagnetization characteristics up to 300 °C.

Second-quadrant demagnetization curves at up to 300 °C for 1-cm cubic samples of the Sm_2Co_{17} type of magnet have been obtained from five manufacturers. NASA Lewis has used such data to study the decrease of the so-called 10-percent-down knee coercivity with increasing temperature and has compared it with the applied demagnetizing H-field needed to produce a given swing ΔB of the magnetic induction below the remanence B_r. From this it was observed that, even for the most promising Sm_2Co_{17} type of commercial material, the margin of safety against accidental demagnetization practically vanished at temperatures above 280 °C and ΔB above $0.8B_r$. In this way our studies have defined the boundary of safe high-temperature



Demagnetization curves at selected temperatures.

operation against some demagnetizing overfield for representative commercial Sm_2Co_{17}. We have also verified that room-temperature performance is not a reliable predictor of properties near 300 °C, where considerable variation was observed with source manufacturer for otherwise comparably specified magnets.

Long-term aging effects on the Sm_2Co_{17} materials as well as temperature effects on the magnetic properties of the $SmCo_5$ type of magnet will be investigated next.

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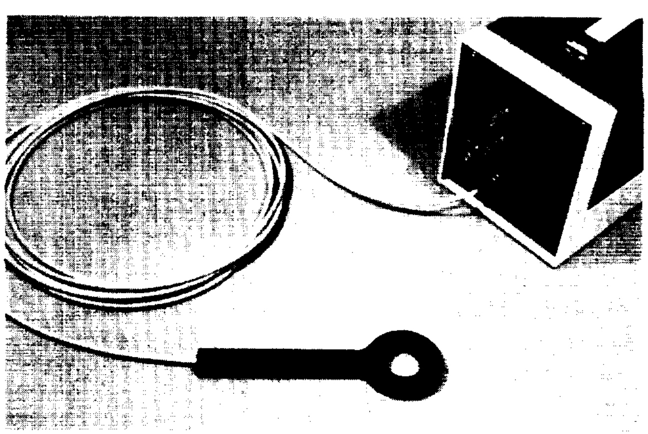
Fiber-Optic Sensors Being Developed for Electrical Measurement

Electrical discharges in spacecraft can produce upsets in onboard electrical systems. On or near the surface of the Earth, lightning flashes and nearby operating electrical machinery can generate similar problems. Often it is desirable to measure electrical current flowing through a conductor, but the conductor is at a very high voltage. These factors cause significant electrical measurement problems that can be solved with fiber-optic sensors.

Under contract to NASA Lewis the National Institute of Standards and Technology at Boulder is developing sensors that make electrical measurements optically and report the measurements to other locations by means of optical fibers. Thus far, early versions of ac current and voltage sensors have been developed. Both types of sensor have excellent isolation, which means that with these sensors it is possible to make a measurement at one location and report it to another location when both locations are at significantly different voltages. The current sensor is intrinsically immune to electromagnetic interference, and both sensors reduce electromagnetic noise typically picked up by connecting wires. The sensor heads can operate over the broad temperature range of –65 to 125 °C. The sensors were designed to operate over a wide range of frequencies including 60-Hz terrestrial, 400-Hz aircraft, and 20-kHz high-frequency aerospace power.



Fiber-optic current sensor and electronics package.

An early current sensor operated throughout severe vibration testing at Lewis, and a voltage sensor is about to undergo vibration tests. Thereafter an advanced current sensor will be developed and later a power sensor that will perform both current and voltage sensing in one sensing head. The fiber-optic electrical sensors will find applications in spacecraft, launch vehicles, aircraft, and Earth-bound electric power systems.

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Small Free-Piston Stirling DIPS Beats RTG's for Robotic Space Missions

High-power-density, free-piston Stirling engine (FPSE) and linear alternator technology can be combined with radioisotope heat sources to produce a compact dynamic isotope power system (DIPS) that is suitable for multihundred-watt space applications and is competitive with advanced radioisotope thermoelectric generators (RTG's).

Unlike earlier DIPS concepts, which were based on closed-cycle Brayton conversion, the small FPSE DIPS can be favorably scaled to multihundred-watt power levels or lower. The

FPSE converter, which is not subject to the tip-clearance-to-swept-area scaling limitation of turbomachinery, remains a high-efficiency converter in sizes ranging from kilowatts down to only a few watts. At multihundred-watt unit size an FPSE can be directly integrated with the Department of Energy general-purpose heat source (GPHS) by means of radiative coupling. Although this integration method is limited to multihundred-watt systems (every GPHS block must have a view of the heater head), a major advantage emerges for FPSE in this power range, since direct integration significantly reduces heat source structure and insulation and eliminates high-temperature, intermediate heat transfer devices.

Recent studies for the Space Exploration Initiative have characterized small Brayton and Stirling DIPS parametrically and compared them over the steady-state output power range 0.2 to 1 kWe. Brayton characterizations, which were based on "mini-BRU" Brayton isotope power system (BIPS) technology, modeled the converter (turbomachinery, ducting, and heat exchangers) by using the Closed Cycle Engine Performance (CCEP) code developed at NASA Lewis. Stirling characterizations were based on the Civil Space Technology Initiative Stirling space power converter and small engine designs developed at NASA Lewis and by its contractor, Mechanical Technologies Inc. They modeled the scaled-down free-piston Stirling engine/linear alternator (20 kg/kWe), which was directly integrated with the GPHS heat source. Direct integration yielded the highest specific power: 11 to 14 W/kg, approximately double that of the other systems at 200 We.

The size and weight of the small FPSE DIPS compare favorably with the next generation of RTG's (Mod-RTG). However, it requires less than a third the isotope fuel. For these reasons the small FPSE DIPS appears to be an attractive alternative to RTG's. If it is developed, it should prove to be a viable candidate for powering the many multihundred-watt robotic missions anticipated within the next three decades for deep space and planet surface exploration. It can extend the high-efficiency advantage of dynamic systems into a power range never previously considered competitive for DIPS. This will result in lower fuel cost and reduced radiological hazard per delivered electrical watt.

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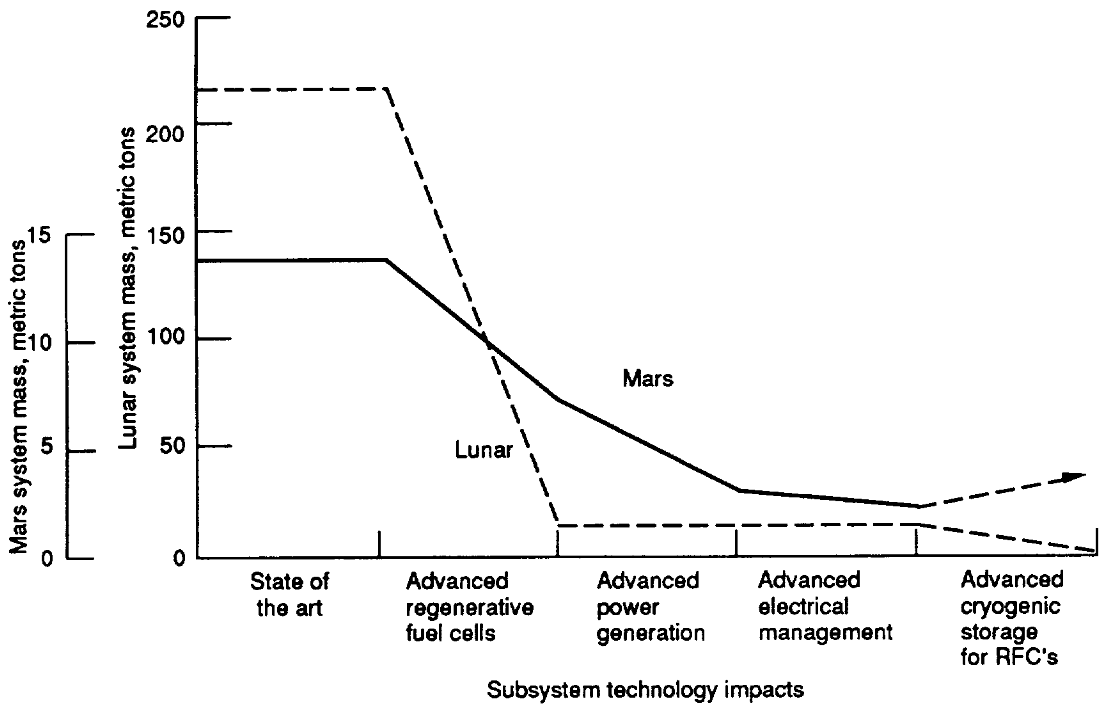
Stationary and Mobile Power Systems Being Developed for Extraterrestrial Missions

NASA is working to develop power technology to a level of readiness sufficient to enable or enhance extraterrestrial surface missions. NASA's planning for the future exploration of the solar system includes precursor piloted missions, outposts, and bases on the Moon and Mars with several types of rover crisscrossing the surface. The high levels of power associated with an operational base will ultimately require stationary reactor power systems. During the installation of these permanent reactor systems, power systems based on solar energy will supply the needed power. Batteries, fuel cells, and isotope-based power systems could provide the power for the rovers needed for construction, transportation, and gathering scientific information across the surface.

Recent definition of stationary power requirements for a lunar mission has shown a steady, unrelenting increase in power demand from 25 kWe initially to 1 MWe for a mature lunar base. In order to meet the initial demands (up to 100 kWe), a series of small (~25 kWe) solar-based power systems will be deployed on the surface of the Moon, followed by an ever-increasing number and complexity of reactor-based power systems. Similar scenarios have been developed for a Martian mission, however, with smaller power demands.

The initial solar-based power systems for lunar and Martian missions will use advanced technology in the areas of power generation (photovoltaic arrays that convert solar power to electricity); energy storage (H_2–O_2 regenerative fuel cells for the 2 weeks of lunar night); and electric power management (controlling the flow of electricity between generation,



Mass of initial extraterrestrial power systems (25-kWe electrical output day and night).

storage, and user bus). Advanced technologies will substantially reduce the mass of the initial power system to a manageable level relative to today's state-of-the-art technology and thus lower the cost of transporting this solar-based power system from Earth to the lunar surface.

Photovoltaic arrays using "tent" deployment schemes have been conceived with a specific power of 300 We/kg. This concept offers a factor-of-6 mass advantage over state-of-the-art concepts for 50-We/kg photovoltaic arrays using standard, flat-plate deployment schemes.

Fuel cell stacks (a critical element in an H_2–O_2 regenerative fuel cell energy storage subsystem) based on updated acid technology are being tested in a data-base gathering effort to confirm the potential of a 4-year operational life goal with minimal maintenance. Advanced alkaline fuel cell catalysts, the life-limiting material in an alkaline fuel cell, have been identified and evaluated in the laboratory with promising results. The efficacy of advanced cryogenic H_2–O_2 storage tanks and associated reliquefaction concepts for use in the regenerative fuel cell subsystem are under serious study for lunar missions because of the potential factor-of-2 mass savings over high-pressure gaseous storage techniques.

Electric power management component issues have been identified. These issues relate to the nonexistence of, and therefore need for, high-power-density and wide-temperature-swing electronic assemblies.

Lunar rover power requirements have also been identified. Since the missions of rovers vary from small 100-We disposable scientific vehicles to multi-tens-of-kilowatt construction and transport vehicles, the rover power technologies of choice will vary. In all cases the power system often represents a high fraction of rover mass (e.g., 20 to 90 percent). The actual percentage depends heavily on the power technology used and also on whether the rover's mission permits recharge by using the existing lunar base infrastructure or whether recharge capability must be totally onboard.

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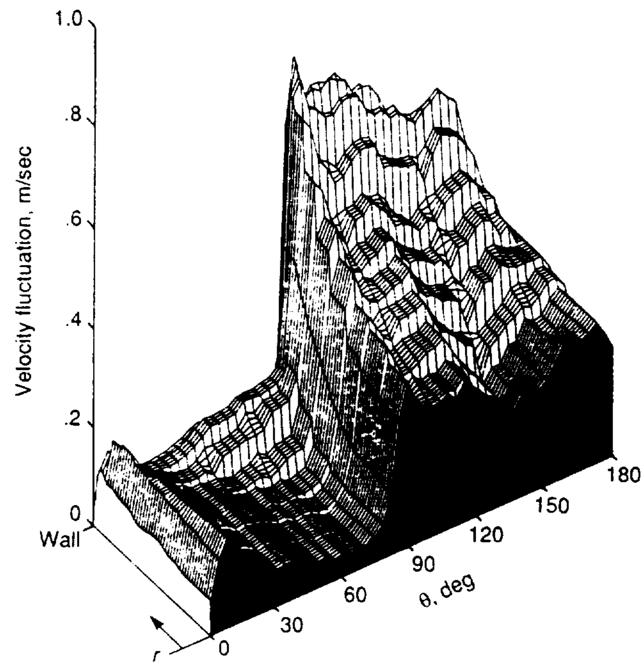
Advances Made in Understanding Stirling Thermodynamic Losses

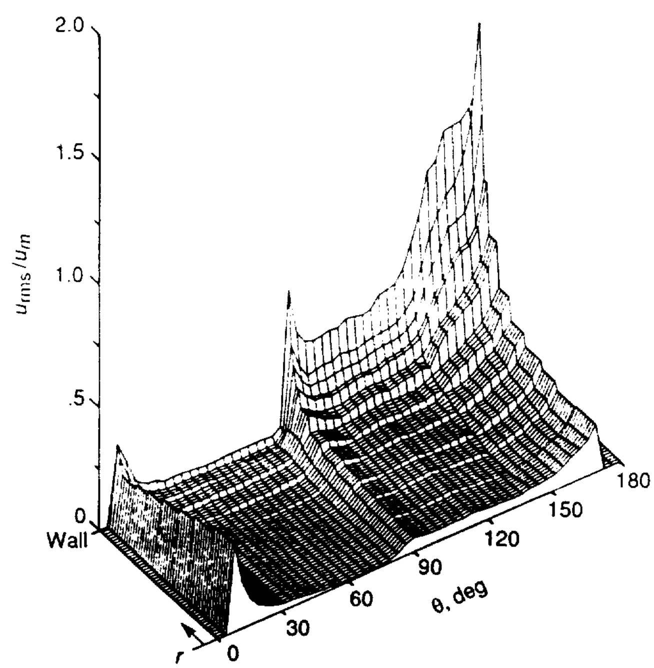
Research efforts are under way to improve characterization of Stirling thermodynamic losses. The research is being conducted primarily on grant by researchers at the University of Minnesota, Cleveland State University, the Massachusetts Institute of Technology, the University of Pittsburgh, and Ohio University. These efforts were started because it seemed likely that shortfalls in Stirling converter performance were in part due to poor thermodynamic loss characterization in the design codes. The goal of the loss research is to improve the accuracy of the one-dimensional flow design codes that support NASA's space and the Department of Energy's terrestrial Stirling engine development programs. The benefits are expected to be improved engine performance with fewer expensive hardware modifications. The technical accomplishment highlighted here is the derivation of a design guideline that is expected to improve engine performance.

Both prediction and measurement accuracy are difficult to achieve in the high-frequency, oscillating-flow, Stirling internal fluid flow and temperature fields. Therefore, several specialized oscillating-flow test rigs have been built to acquire needed data. The geometry of these rigs was scaled to facilitate accurate unsteady measurements while maintaining appropriate ranges of dimensionless parameters. In coordination with the rig tests two-dimensional modeling is attempting to elucidate the physics of fluid flow and heat transfer. These test results and two-dimensional computations have suggested methods of improving engine performance.

Recent loss research has strengthened the perception that using steady-flow heat transfer and friction factor correlations in heat-exchanger flow passages leads to significant errors in predicting engine performance. These errors seem largely due to inaccurate prediction of laminar-to-turbulent flow transitions. Oscillating-flow rig tests have shown that flow acceleration delays these transitions. The net result is that flow stays laminar over a larger portion of the high-Reynolds-number part of the Stirling cycle than is indicated by steady-flow correlations. This causes both heat transfer and engine performance to suffer. Some of the oscillating-flow test results that are providing insights into the laminar-to-



Root-mean-square velocity fluctuation about the ensemble average. Dark surface is the plane of the centerline, y/d = 0.5.



Normalized turbulence intensity.

turbulent "state" of the fluid over an engine cycle are three-dimensional plots of University of Minnesota flow rig data. These data were taken at values of dimensionless parameters similar to the design values of the Space Power Research Stirling Engine (SPRE).

An obvious, but difficult, way to improve prediction accuracy is to develop new unsteady correlations. However, it appears that a simpler way to improve prediction accuracy *and* engine performance would be to maintain turbulence over essentially all of the engine cycle so that accurate prediction of transition would not be important. Computer code calculations suggest that, for the SPRE, failure to maintain turbulence may be reducing power and efficiency as much as 10 and 5 percent, respectively.

Test results and two-dimensional computations suggest that design guidelines should require the fluid stroke (over the cycle) in the heater and cooler flow passages to be greater than the flow passage length. Then ingested turbulent fluid at flow reversal and boundary layer separation at sharp tube ends help maintain turbulence. (Current design code correlations do not account for these turbulence-producing mechanisms.) This change improves heat transfer in heaters and coolers with some increase in viscous loss. (Viscous loss in the heaters and coolers is usually not a "major driver," since most of the viscous loss is usually in the regenerator heat exchanger.) Attempts are under way to define SPRE tests that could, roughly, check the sensitivity of engine performance to the duration of turbulent flow over an engine cycle.

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Solar Dynamic Space Power Demonstrator Design Uses a Free-Piston Stirling Power Converter

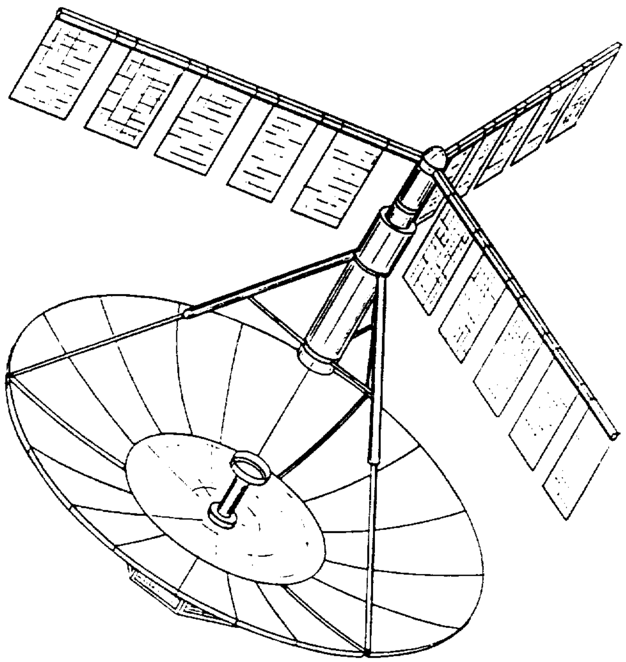
A team of NASA Lewis engineers and scientists has produced a conceptual design for a 1.5-kW Solar Dynamic Space Experiment (SDSE). This experiment is intended to demonstrate the feasibility of a dynamic power system operating in space. The design strategy called for an integrated system approach with 25 percent system efficiency and high reliability. System tradeoff studies were performed and updated throughout the design process to guide the design of the individual subsystems. These subsystems include the concentrator, the receiver, the free-piston Stirling engine with a linear alternator, the radiator, and the power management and control system. Supplemental tasks included orbit analysis and a failure modes and effects analysis.

Mission specifications called for the SDSE to be placed into low Earth orbit by an expendable launch vehicle, thus the deployable configuration. Electric power output of 1.5 kW will be generated throughout the orbit, during the sunlight phase of the orbit and also while in eclipse. The mission is intended to last for 1 year. As determined through system optimization studies, the Stirling power converter is to resonate at 80 Hz with a 2.7 temperature ratio.

Within the aforementioned design goals, the design philosophy encouraged creativity, which resulted in numerous innovative features. Key features of some subsystems include the following:

(1) A deployable concentrator with a rigid center section is surrounded by hinged petals. Three evenly spaced discontinuities in the mirror surface are aligned with the three supporting struts and three radiator arms to avoid shadowing the concentrator. Shadows on the concentrator could distort the mirror surface.

(2) A solar receiver with 10 sodium heat pipes is used to absorb the concentrated solar energy and transport it either to the Stirling converter or to thermal energy storage material. The power converter operates on stored thermal energy while in the Earth's shadow. Heat is transferred to the Stirling power converter through the 10 primary heat pipes; a secondary cavity heat pipe adjacent to the power converter minimizes thermal maldistribution and the impact of the failure of a primary heat pipe.



SDSE in operational configuration.

(3) A Stirling power converter consisting of a free-piston Stirling engine with an integrated linear alternator is used to convert thermal energy to electric power. A vibration damper is contained within the engine housing to minimize vibration. A linear driver with a closed-loop controller is used to reduce the residual vibration to a minuscule level. Noncontact gas bearings are used for all moving elements to achieve long life.

(4) For redundancy the radiator system has three independent pumped loops, one for each radiator arm. Water-filled titanium heat pipes transport heat from each pumped loop. These finned heat pipes are made of a high-thermal-conductivity, low-mass graphite-aluminum composite. The composite is tailored to yield thermal expansion properties consistent with the titanium heat pipes.

(5) Control system duties include initiating operation of the system and responding to a potential system perturbation, in addition to monitoring engine temperature and stroke during normal operation. This subsystem utilizes a resistive electric load to modulate the engine and to dissipate the power output from the linear alternator. Consistent with the goal of this experiment, the power absorbed in the load resistor is radiated to space. In future applications the power will be used in a mission.

All power systems flown to date have been passive devices, such as photovoltaic arrays or radioisotope thermal generators. Stirling power converters have been shown to have the potential to increase system efficiency while also reducing specific mass relative to current technology. Stirling power converter systems have been proposed over a wide range of power levels (tens of watts to multimegawatts) with either nuclear, solar, or isotope heat sources. These power converters have the potential for long life through the use of noncontact bearings for the moving components. The SDSE will be used to demonstrate the feasibility of a dynamic power system operating in space and to explore operational characteristics not encountered in terrestrial applications.

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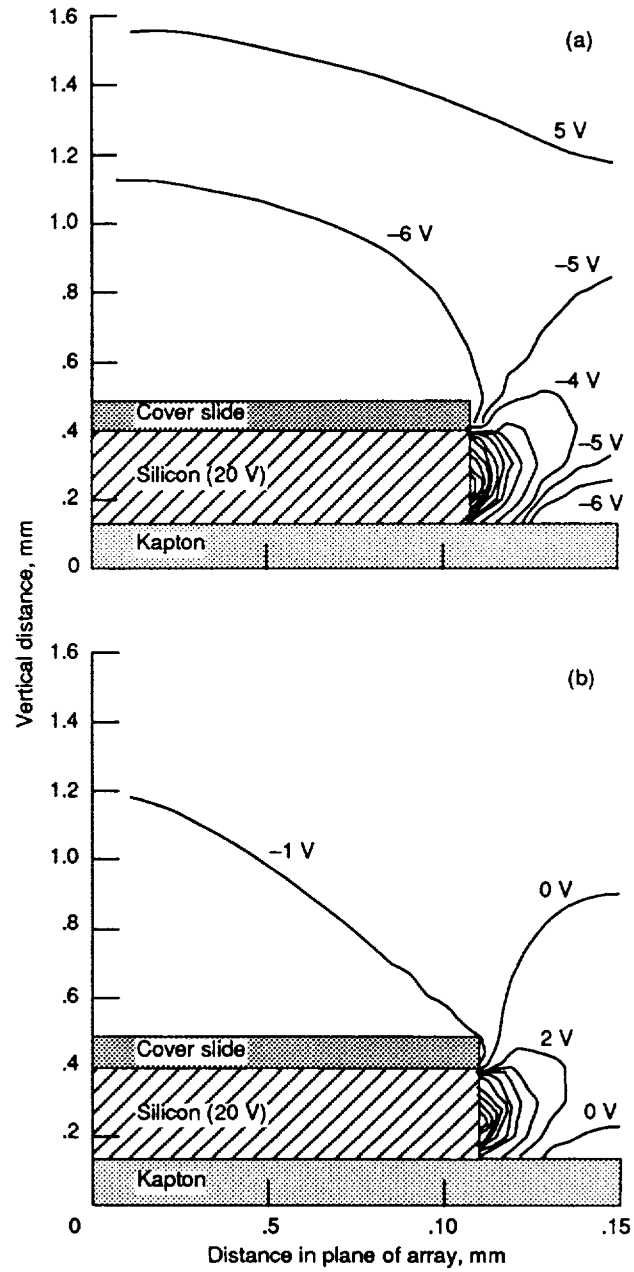
NASCAP/LEO Models Electron Current Collection From Space Plasma by Space Station *Freedom* Solar Cells

As new technologies are developed and old technologies operate under new conditions, new issues become important in evaluating the compatibility of different system elements. It is difficult to accurately reproduce all the essential features of the space environment during ground tests. Instead of using ground test results directly to confirm system behavior in the space environment, it is necessary to compare ground test results with environmental interaction models that have been validated both in extensive ground experiments and in space experiments. Then the models must be used to extrapolate system operation to space conditions.

In 1989, Space Station *Freedom* (SSF) electric power system designers tested a panel of solar arrays representative of those that will produce the electric power for SSF in low Earth orbit. The tests were performed in the simulated space plasma of a ground-based vacuum chamber as part of the SSF solar array plasma tests performed at NASA Lewis. Electron current collection from the surrounding plasma by the solar cell circuit in these tests was much lower than expected. It was important to understand this result because the electron collection of the array relative to its plasma ion collection will determine how much the SSF system electrical ground potential will differ from the electrical potential of the ambient plasma, which in turn affects the magnitude of several important environmental interactions. There are plans to ground the SSF electrical system to the negative side of the solar array so that if the electron current collection is high, the SSF ground potential will be removed from the plasma potential by an amount close to the total voltage generated by the solar arrays (160 V, in the SSF case). If the electron collection is low, SSF ground potential may be a few tens of volts closer to the potential of the ambient plasma, lessening the undesirable environmental effects.

The Space Environment Effects Branch at NASA Lewis has used a three-dimensional computer simulation program called NASCAP/LEO, previously developed and validated under Lewis auspices, to understand the anomalously low electron collection current observed in the SSF solar array plasma tests. The new-technology SSF solar cells do not have exposed interconnects that will collect large currents from the plasma. In these cells current is collected from the plasma only along the cell edges. The relatively high electron temperatures of the plasma produced during the ground tests caused the surfaces of the solar array cover slides to charge sufficiently negative that the outside plasma was shielded from the positive potentials existing in the gaps between the cells on the positive end of the solar array string. A potential barrier formed to prevent plasma electrons from entering the gap. Extrapolation of the model to space conditions, where the electron temperatures are much lower, suggests that the surface potentials will not be sufficiently negative to prevent electron collection in the space environment. The potential barrier, if it exists, is much lower. No potential barrier exists for ion collection to cells more negative than the plasma potential.



(a) Ground test plasma conditions.
(b) Space plasma conditions.

NASCAP/LEO-generated equipotential contours for Space Station Freedom solar cells.

It was concluded that electron currents available in space will be higher than those observed in the ground tests and that the solar array, along with the rest of the SSF, will float more negative with respect to the surrounding space plasma than was observed in the ground tests. This will be important in evaluating the impact of plasma interactions, which can result, among other things, in sputtering of surface coatings and dielectric breakdown of surface anodization.

These conclusions will be tested during additional ground testing presently scheduled for mid-1992, which will attempt to more closely simulate the important features of the space environment, and in a flight experiment (the Solar Array Module Plasma Interaction Experiment) scheduled to fly aboard the space shuttle in 1993.

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Leveling Coatings Improve the Optical Performance and Atomic Oxygen Durability of Solar Concentrator Materials

Optical materials such as reflectors (mirrors) or refractors (Fresnel lenses) will be used on Space Station *Freedom* to focus the Sun's energy onto solar dynamic or photovoltaic power systems. These optical materials must maintain their optical performance in the harsh environment of low Earth orbit (LEO). The predominant species in the LEO environment is atomic oxygen, which is extremely reactive and will corrode oxidizable materials. Therefore, materials that are susceptible to oxidation need to be protected. Unfortunately, the protective coatings that are applied contain many defects, providing a pathway for atomic oxygen to enter and catastrophically attack the sensitive material below. It has been determined that the reason for these defects is largely the microscopically rough substrate surface.

Coupons with and without a surface-tension-leveling coating on top of a rough optical substrate (beneath the atomic-oxygen-protective coating) were tested in simulated atomic oxygen environments. The leveling coating improved the initial optical properties and decreased the defect density (by an order of magnitude) of subsequent coatings. Improved optical performance and atomic oxygen durability of optical materials will result in greater efficiency and longer life of power systems.

Current in-house research efforts at NASA Lewis include plans for the automated application of a number of different leveling coatings on a variety of optical substrates in a dust-free environment. Protective coatings will then be applied to these coupons and they will be evaluated for their optical performance and atomic oxygen durability.

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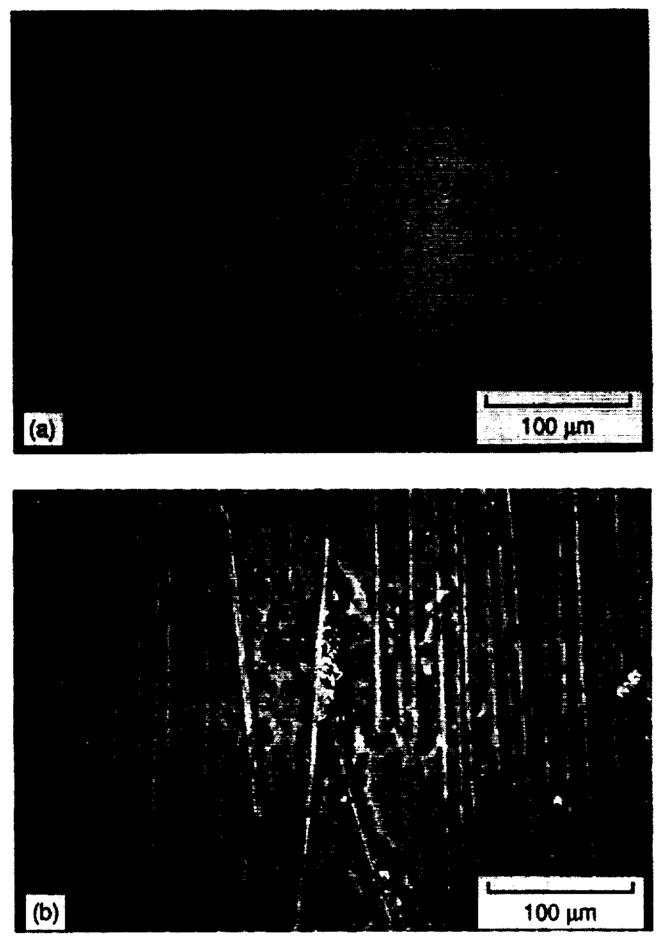


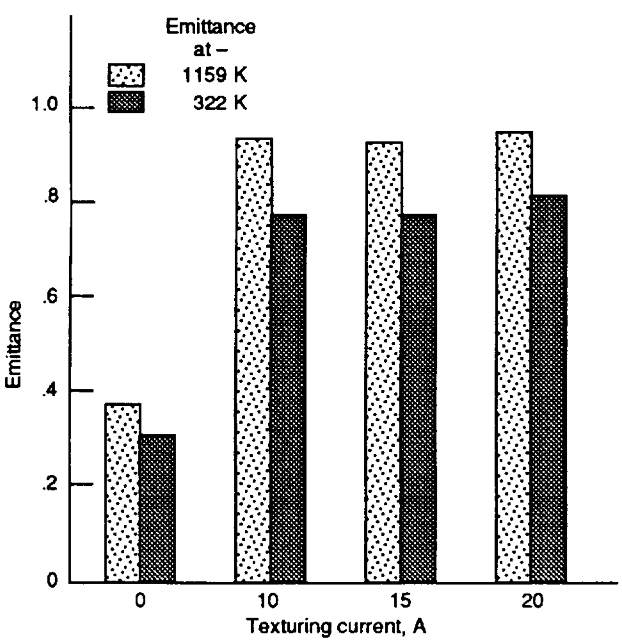
(a) With a leveling coating.
(b) Without a leveling coating.

Atomic-oxygen-exposed, aluminum-coated graphite epoxy with and without leveling coatings. Dark areas are atomic oxygen damage.

Thermal Emittance of Graphite/Copper Enhanced for High-Temperature, Space-Based Radiators

Space and surface nuclear power systems will require radiators that can efficiently remove waste heat to maintain the desired operating conditions. Typical radiator operating temperatures are 700 to 900 K for thermoelectric systems and 525 to 650 K for Stirling engines. Thermal emittances of 0.85 or greater are desired in order to minimize the radiator area needed while maximizing the waste heat rejection at these temperatures. An attractive candidate material for space-based nuclear radiator systems is a graphite/copper composite. Such composites typically have thermal emittances of approximately 0.3 at 322 K and 0.37 at 1159 K, which are too low for the desired applications. Altering the surface morphology of the radiator can produce the emittance enhancement needed.

NASA Lewis is investigating the feasibility of arc texturing of graphite/copper for increasing the thermal emittance of a variety of radiator materials. Initial results demonstrate that altering the surface morphology increases emittance from initial values of approximately 0.34 to near 0.85 at the desired operating temperatures. The resulting texture is a stable and integral part of the surface, making it attractive for many high-temperature space applications.



Arc-textured graphite/copper at a constant frequency of 60 Hz.

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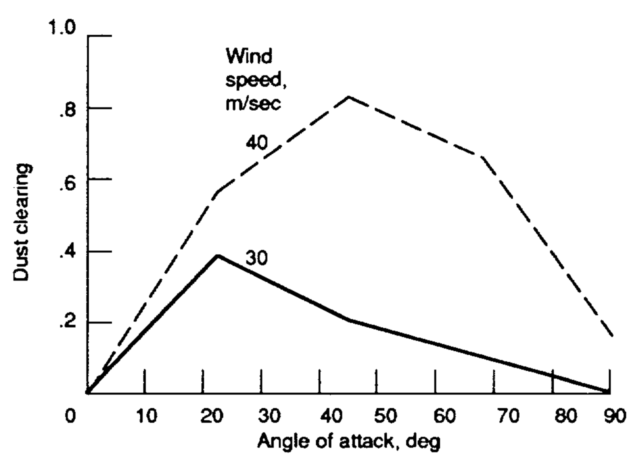
Dust Removal From Power Systems in the Martian Environment Evaluated

Power systems that are erected on the Martian surface must be able to withstand the local environment if they are to be reliable over long periods of time. One of the environmental hazards of the Martian surface is dust. Large quantities of dust are elevated during planet-wide dust storms that occur nearly every southern spring. Not only does the dust block light (decreasing the efficiency of photovoltaic arrays) during the storm, but also after the storm a fine coating of dust is deposited on everything, including the surfaces of photovoltaic arrays and radiators.

NASA Lewis is evaluating the effects of this dust coating on photovoltaic arrays and radiator surfaces. In the initial series of experiments, dust was deposited on photovoltaic cover slide materials and on textured radiator material surfaces and then removed in the Martian Surface Wind Tunnel at NASA Ames Research Center. This wind



Dust clearing from surfaces in Martian-like winds.

tunnel operates at Martian pressures (1000 Pa) and at velocities ranging from 20 to 100 m/sec. The effects of angle of attack, turbulence, surface material, and wind velocity on the ability of the wind to clear dust from the surface were evaluated by comparing the specular transmittance initially, after dusting, and after wind action. The most sensitive parameters proved to be wind velocity and angle of attack. The optimum angle for dust clearing appeared to be nearly 45°, and at that angle the threshold velocity for basaltic dust (similar to that found on Mars) was between 30 and 40 m/sec. Winds this high were measured at the two Viking lander sights less than 1 percent of the time; therefore, photovoltaic cells and radiator surfaces are not likely to be self-clearing in the tenuous Martian winds.

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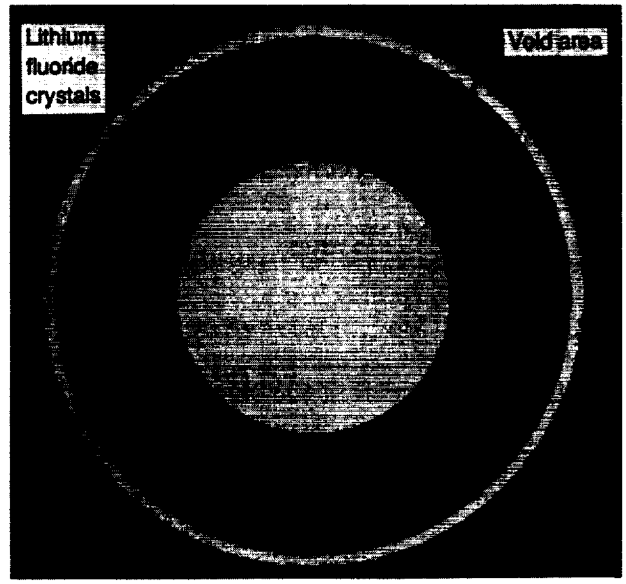
Tomography Used as a Nondestructive Technique to Examine Voids in a Thermal Energy Storage Container

Voids that occur in a salt used as a thermal storage material in solar dynamic systems have been a primary concern for designers of solar heat receivers. Voids in a critical area can cause overheating or distortion and can cause failure of the container material. Current NASA Lewis investigations into void behavior include ground testing and, for the first time, an extended microgravity flight test. The need to know void size, shape, and location before and after each test is critical. Tomography is a tool that makes possible an accurate and detailed image of the salt and the void without physically penetrating the salt container.

Tomography, or more precisely computerized tomography (CT), is a technique first introduced in the early 1960's. It gained widespread use in the medical field in the 1970's and became known as CAT scans. Industrial applications were introduced in the late 1970's and have been growing ever since.



Computerized tomography cross section of annular canister showing void areas in lithium fluoride crystals.

In CT, an object is placed between a collimated x-ray fan beam and an x-ray-sensitive detector. X-ray intensity measurements are made by the detector as the object is fully rotated within the x-ray fan beam. A cross-sectional image is then computer generated from the data to provide a highly accurate internal view of the "slice" of the object.

A significant breakthrough in the x-ray source and detector technologies has enabled resolution of the image to better than 25 μm. This high resolution permits the detection of salt void pockets as well as of the crystal structure throughout the thermal energy storage volume.

The CT equipment used in the NASA Lewis investigations was developed by the Advanced Research and Applications Corporation (ARACOR) at the Air Force Wright Laboratory in Dayton, Ohio, as part of an effort to extend the range of applications that can utilize CT technology.

The accompanying figure is a CT cross section of the annulus structure that contains the thermal energy storage material (lithium fluoride). The image shows areas of the void and the crystal structure of the salt. The void is the result of the annulus having been filled under normal gravity and is not indicative of what may be expected from cyclic heating (melting the salt) and cooling (solidifying the salt) in microgravity flight. The crystal structure shows innumerable cracks and fissures that developed when the lithium fluoride cooled and solidified. The CT shown here in black and white is taken from a color scan. Color adds another dimension of contrast to this technique.

The CT technology has demonstrated that it can satisfy the requirement to obtain accurate and detailed patterns of voids and the salt crystal structure.

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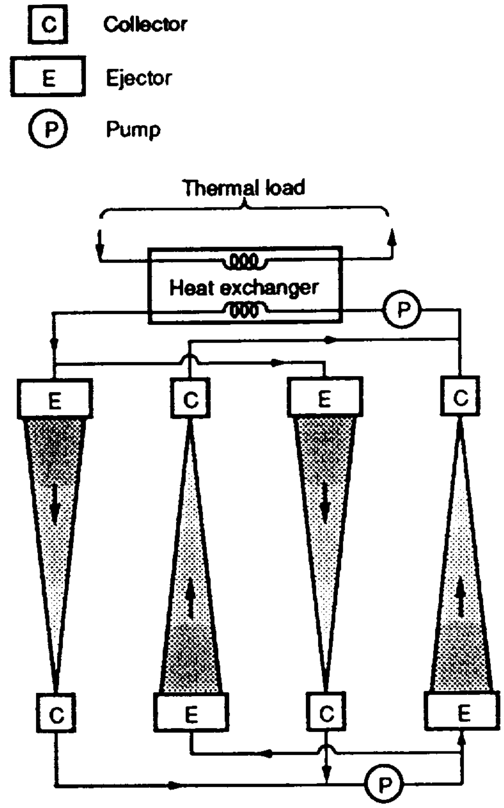
Stability of Liquid-Sheet Radiator Investigated

Using a flowing, thin sheet as the radiating surface results in a low-mass space radiator immune to micrometeoroid damage. A unique characteristic of thin-sheet fluid flow is that the flow coalesces to a point, resulting in a triangular-shaped sheet. Surface tension forces at the edges of the sheet cause cylinders to form that grow in diameter in the flow direction. As the cylinders grow, the sheet narrows to satisfy conservation of mass. The end cylinders eventually meet at a point. This coalescing of the flow to a point is ideal for collecting the flow in a space radiator.

The dependence of sheet length-to-width ratio L/W on the flow variables has been experimentally determined. These results agree with the theoretical prediction $L/W = \sqrt{We/8}$, where $We = \rho \tau w^2/\sigma$ is the Weber number, ρ is the fluid density, τ is the sheet thickness, w^2 is the flow velocity, and σ is the surface tension. Currently, the stability of the sheet flow is being investigated. Deviations from a uniform thickness can cause insta-bilities that produce holes in the sheet. The stability study is directed at understanding this hole formation mechanism.

For low-temperature (<400 K) applications, a Dow-Corning silicone oil has been identified as suitable for space operation. However, at high temperatures only liquid metals have low enough vapor pressure to operate at vacuum conditions without significant evaporation losses. The emissivity of a sheet of the Dow-Corning oil has been calculated by using experimentally measured spectral transmission data. Results of that calculation predict an emissivity greater than 0.8 for sheets thicker than 200 μm in the 300 to 400 K temperature range. These emissivities are suitable for radiators in space.



Parallel, connected liquid sheet radiator system.

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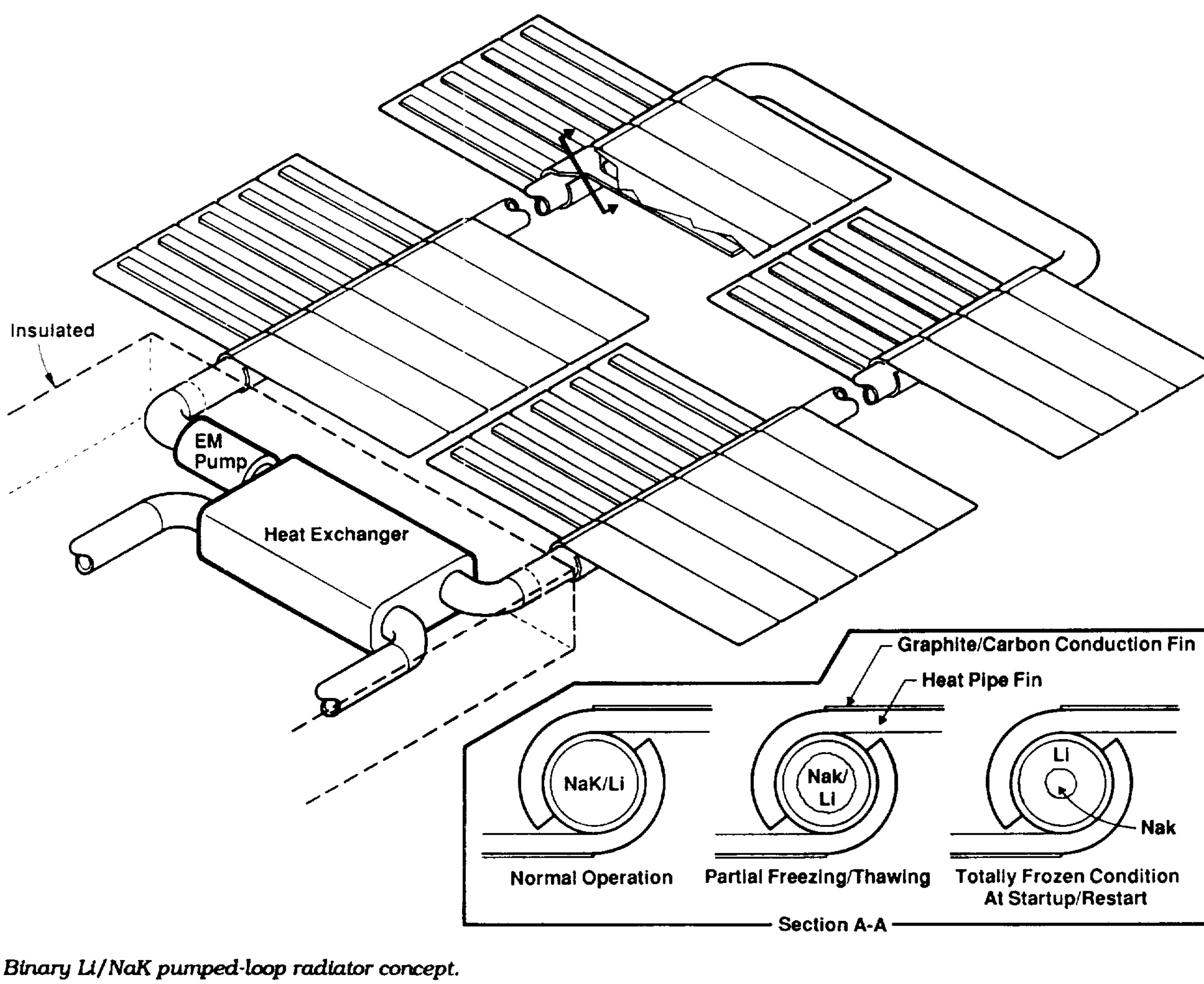
Feasibility of Binary Lithium/NaK Pumped-Loop Radiator Concept Demonstrated

Space power systems that convert heat energy to electric (or work) energy require that the portion of heat energy which cannot be converted to work be rejected by radiative heat transfer to the space environment. The effective temperature of this environment ranges from about 3 K for interstellar space to an average of 250 K in low Earth orbit, and to over 300 K for a lunar day. The radiator temperature depends on the particular power system used, and radiative heat rejection to the space environment is greatly enhanced by using lightweight, high-conductivity graphite carbon fins.

For power systems such as the free-piston Stirling engine (FPSE), radiator temperatures range from 500 to 600 K. NASA Lewis is currently developing an innovative binary Li/NaK pumped-loop radiator concept for this temperature range through a contract with Space Power, Inc.

Development of this radiator concept is motivated by a desire to avoid the problems associated with alternative radiator concepts that use pumped loops or heat pipes with mercury as the working fluid. Moreover, the binary Li/NaK mixture combines the high heat capacity and low pumping power of lithium (Li) with the liquid pumping capability of sodium potassium (NaK) down to fluid



Binary Li/NaK pumped-loop radiator concept.

temperatures of −12 °C, a feature that will provide the key for successful initial startup and restart of the power system in space.

During startup operation liquid NaK would flow through the inner cores of radiator tubes, in hydraulic contact with frozen layers of lithium coating the inner surface of these tubes. As the NaK is heated during power system startup, it will eventually melt the solid lithium shells by direct-contact, force-convection heat transfer and will progressively mix with the NaK to eventually form the all-liquid Li/NaK coolant. Conversely, upon power shutdown the molten lithium will selectively cold-trap out of the Li/NaK mixture onto the radiator passage inner surfaces, as they cool below the lithium freezing point of 179 °C, while the sodium potassium continues to be pumped in its liquid state through the cores of the radiator passages.

Initial tests conducted so far have demonstrated the feasibility of this concept, both in the freeze (cold trap) and thaw modes. Current efforts focus on widening and mapping the operating envelope prior to eventual flight testing in collaboration with the Air Force's Phillips Laboratory.

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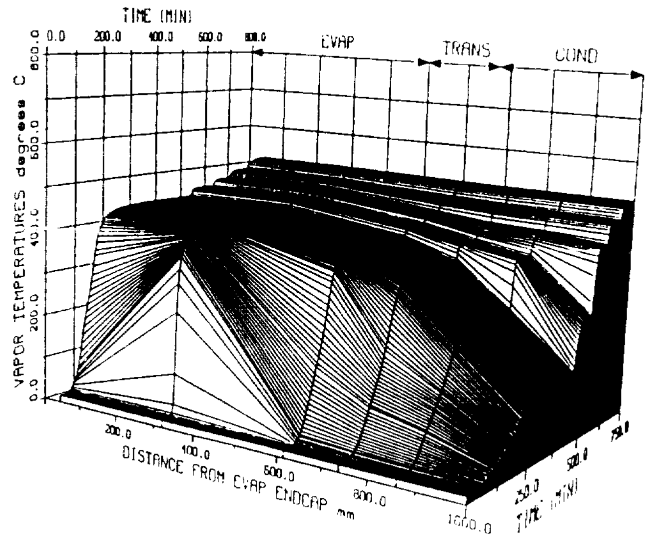
Heat-Pipe Computer Codes Developed

It is necessary to predict heat-pipe operating limits in order to design heat-pipe radiators for space applications. To this end, NASA Lewis has developed steady-state and transient heat-pipe computer codes as analytical tools for calculating performance for a wide range of heat-pipe geometries, wick structures, containment envelope and wick materials, and working fluids.

The steady-state heat-pipe code has an improved vapor flow algorithm that gives it a wide range of capabilities, such as calculating heat-pipe limits for cases with multiple evaporator, adiabatic, and condenser sections. Also the code can handle a variety of external boundary conditions, such as variable heat loads or variable temperature profiles. The code was written at NASA Lewis and has been documented. Experiments will be performed at Lewis to validate the code.



Vapor temperature profiles with evaporators 2 and 3 active, operation in vacuum, a fluid charge of 43 g, and evaporator elevation of 0°.

Transient heat-pipe codes under development have the capability to predict transient heat-pipe performance for a variety of conditions. The analysis is multidimensional and can be applied to nonconventional heat pipes with uniform or nonuniform heat distribution. The work is ongoing at three universities: University of California, Los Angeles; Wright State University; and the University of New Mexico.

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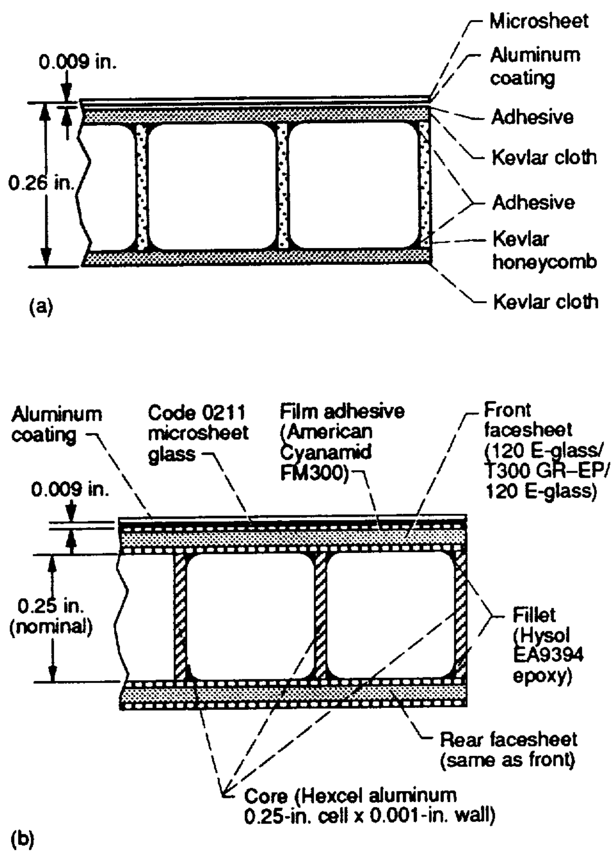
Advanced Microsheet Glass Concentrator Holds Promise

Solar dynamic space power systems require efficient components to minimize their weight and size, which affect packaging for launch. Primary design requirements for an advanced solar concentrator are high optical accuracy and material–space environment compatibility.

These requirements translate into high geometric and surface accuracy and compatibility with atomic oxygen, ultraviolet, vacuum, and other radiation elements of the space environment. Traditionally, the approach to a high surface accuracy has involved a metallic substrate overcoated with a polymer leveling coating to provide a smooth (glass-like) and reflective surface. Since the leveling coating was intended to emulate the optical surface properties of glass, a program was begun at NASA Lewis to investigate the use of microsheet glass for high-efficiency solar concentrators. Concentrator concepts were developed in house and on contract by Hughes Danbury Optical Systems (formerly Perkin-Elmer Corporation of Danbury, Connecticut).



(a) Glass/Kevlar.
(b) Glass/aluminum (redesigned).

Reflector panel configurations.

Microsheet glass is the name given to a family of soda-lime glasses ranging in thickness from 1 to 20 mils. It is available at a maximum width of 14 in. and an indefinite length. Glass is an excellent candidate for space solar concentrators because of its outstanding optical properties, its durability in a space environment, and its very smooth surface. Glass is widely used in the terrestrial sector to produce highly accurate mirrors. For example, McDonnell Douglas has fabricated a 25-ft heliostat concentrator of 0.7-mm-thick glass that has less than 1 mrad of surface waviness and a reflectance greater than 90 percent. Glass is not degraded severely over time by the atomic oxygen in space, and certain compositions of glass doped with cerium are not affected by ultraviolet radiation.

In 1986 the then Perkin-Elmer Corporation began a study for NASA Lewis to investigate the manufacturability of an extremely lightweight, self-supporting, and highly reflective subscale concentrator panel suitable for use in space. An initial panel design used microsheet glass to protect the panel from atomic oxygen while providing a smooth, highly specular reflective surface. The panel was fabricated by sandwiching Kevlar honeycomb between two Kevlar facesheets with microsheet glass (aluminized on the back side) bonded to one of the Kevlar facesheets.

A series of atomic oxygen asher tests were performed at NASA Lewis on a 4-in.- square microsheet glass/Kevlar composite coupon to determine the extent to which microsheet glass could protect the Kevlar substrate, the facesheets, and the adhesives from atomic oxygen reaction. The coupon was cut into four sections; three sections were ashed for 432.5 hr (approximately equivalent to 1.5 years on Space Station *Freedom*), and the other was held as a control. The three ashed sections differed in that one had that portion of the top surface not covered by glass and its edges protected by aluminum tape, the second was unprotected, and the third was unprotected with a crack in the glass. The protected sample experienced a 4.92 percent mass loss; the unprotected sample had a 14.23 percent loss; and the unprotected sample with the cracked glass had a 15.72 percent loss.

These results led NASA to redirect its efforts to a follow-on activity to design a panel that would be inherently compatible with the natural environment in low Earth orbit. Kevlar honeycomb was replaced by aluminum honeycomb core, the Kevlar facesheets were replaced by fiberglass/epoxy composite facesheets, and the microsheet glass was aluminized on its front side rather than on its back side.

The Hughes Danbury Optical Systems Corporation successfully fabricated 12-in.-diameter panels with a parabolic contour to these revised specifications. These panels were subjected to over 20 thermal cycles, with no signs of degradation. In a fully integrated concentrator these panels approach the NASA technology goals for mass and optical performance.

The Advanced Microsheet Glass Program holds promise for achieving the objectives of the Advanced Solar Dynamic Concentrator Program. The NASA Lewis in-house program, with the support of Hughes Danbury Optical Systems, is developing the technology required for space concentrators that are lightweight, highly reflective, highly accurate, scalable, and long lived (7 to 10 years).

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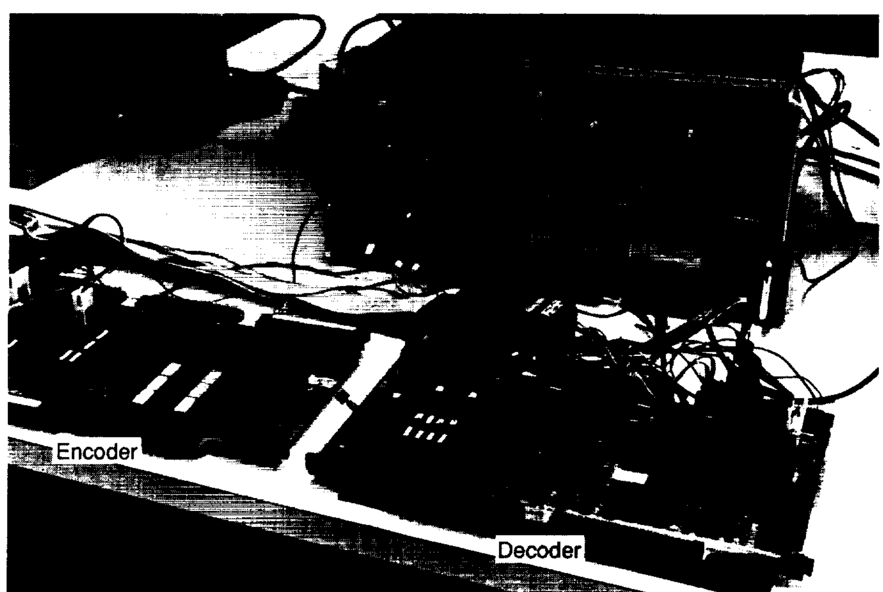
Space Electronics

New Technique Compresses Video Data

NASA Lewis has an ongoing research activity that is focused on developing video data compression technology for transmitting image data over space communications links in a bandwidth-efficient manner. Such development will result in greater orbit/spectrum capacity and lower space segment costs. To this end, a video compression technique (patent pending) has been developed that provides a substantial reduction in the required transmitted data rate, allows relative hardware simplicity, and provides excellent reconstructed image quality.

The technique uses differential pulse code modulation (DPCM), a sophisticated multilevel Huffman encoding process, and a unique nonadaptive prediction that improves edge performance. It is designed to compress standard National Television Systems Committee (NTSC) composite color television signals. A nearly 5:1 compression of the composite signal is achieved (compared with straight PCM encoding). Operation at NTSC video rates (30 frames per second) is made possible by the relatively simple nature of the approach. The technique was developed entirely in house by using computer simulation for initial investigation and refinement.



Breadboard enhanced DPCM video codec.

Breadboard hardware was then developed to prove the feasibility of the approach. The hardware is currently undergoing redesign to incorporate audio and ancillary data transmission capabilities and to take advantage of large-scale integrated circuit technology.

Bibliography

Shalkhauser, M.J.; and Whyte, W.A.: Digital CODEC for Real-Time Processing of Broadcast Quality Video Signals at 1.8 Bits/Pixel. GLOBECOM '89, Vol. 1, IEEE, 1989, pp. 242-249. (Also NASA TM-102325.)

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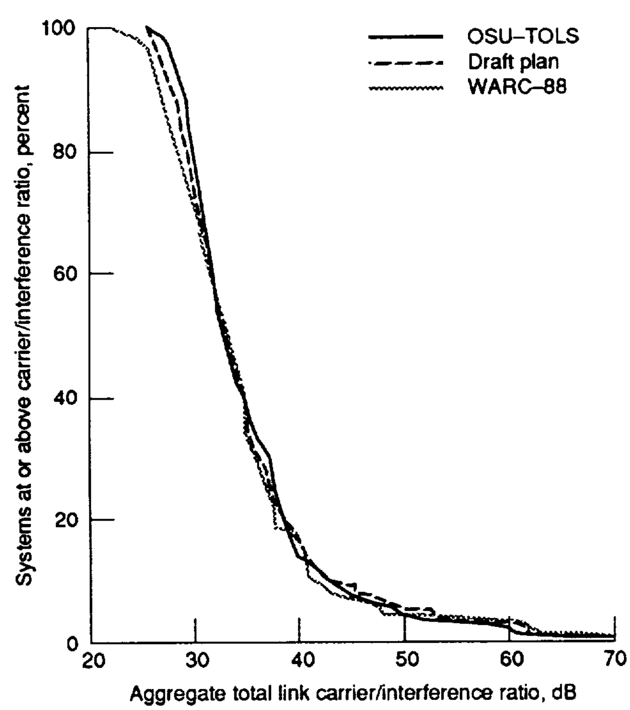
Orbit/Spectrum Utilization Software Developed

NASA has historically supported United States preparations for and involvement in international conferences dealing with the planning and utilization of the geostationary orbit (GSO) resource. The conferences are sponsored by the International Telecommunications Union (ITU), and the results carry the power of international law. Planning for equitable worldwide use of the orbit/spectrum resource is a very complex process involving both technical and political issues. The Ohio State University, under grant to NASA Lewis, has developed a software program for conducting satellite plan synthesis to aid in this complex planning process.

The general form of the satellite plan synthesis problem might be stated as follows: Given constraints imposed by physical system limitations (e.g., service arc limits for each satellite system) and technical considerations (e.g., protection criteria), determine orbital positions for all satellites that allow the necessary constraints to be satisfied. The satellite plan synthesis problem has been recognized as a two-stage problem—first, of ordering the satellites within the GSO; then, of determining satisfactory satellite locations. Ordering the satellites is the more critical stage in achieving solutions to complex planning problems. The Ohio State University (OSU) has developed a set of heuristic procedures that provide a variety of satellite orderings which can allow greater exploration of the solution space for the satellite plan synthesis problem than alternative procedures used in the past. The ability to efficiently examine a significantly greater number of orderings results in superior solutions being obtained with the OSU heuristics than with alternative procedures. The figure shows the results of one of the OSU heuristics, OSU-TOLS (Orbit Spectrum Utilization—Technique for Ordering Locations of Satellites), applied to a worldwide planning scenario. These results are compared against WARC-88 (1988 World Administrative Radio Conference) planning conference results, which were generated by using an alternative synthesis procedure (draft plan curve) and subsequent manual manipulation (WARC-88 curve). OSU-TOLS provides a superior solution without need for manual manipulation. An additional, very significant feature of the OSU planning tool is



Aggregate interference analysis results for worldwide planning scenario.

its relative computational speed. Planning solutions requiring hours of computer time when using alternative procedures can be accomplished in a matter of seconds. The International Frequency Registration Board (IFRB), which is responsible for developing the software used by ITU planning conferences, is very interested in the OSU software. OSU will conclude this research effort with the presentation of their final report in February 1991.

Bibliography

Heyward, A.O., et al.: Application of Heuristic Satellite Plan Synthesis Algorithms to Requirements of the WARC-88 Allotment Plan. 13th AIAA International Communication Satellite Systems Conference and Exhibit, Part 1, AIAA, 1990, pp. 311-321. (Also NASA TM-102479.)

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High-Efficiency Traveling-Wave-Tube Amplifiers Being Developed for Deep-Space Communications

Ongoing programs at NASA Lewis continue to provide the technologies needed for high-efficiency, millimeter-wave traveling-wave-tube amplifiers (TWTA's) for planned NASA deep-space missions. A traveling-wave tube (TWT) is an electronic device in which an electron beam traveling in a vacuum amplifies a weak radiofrequency (RF) signal, typically increasing the power in the output signal so that it is 100,000 times greater than the input power. The TWT accomplishes this by converting the kinetic energy of the electron beam into RF electric energy.

Traveling-wave-tube amplifier.

A current objective of this effort is to develop, in a contractual and cooperative effort with Hughes Aircraft Company, a very high-efficiency, high-data-rate TWTA operating in Ka band (32 GHz) for the Cassini mission to Saturn planned for launch in 1996. The required RF power output of the TWTA is 7 W; the dc input power to the electronic power conditioner cannot exceed 20 W. Achieving this performance goal will more than double the efficiency of Ka-band TWTA's presently available at this power level and will permit the transmission to Earth of all the data produced in the Cassini mission. In order to accomplish this significant increase in efficiency, several Lewis-developed technologies involving computer-aided design and experimental development efforts have been incorporated into the TWTA. These advances include improving the interaction between the electron beam and the radio wave as well as maximizing the recovery of the remaining kinetic energy in the electron beam by means of an electron collector.

An advanced interaction section with a Lewis-designed dynamic velocity taper (DVT) is a feature of the TWT. This "tapering" results in better synchronization between the radio wave and the electron beam. The design of a high-efficiency multistage depressed collector (MDC) has also been contributed by Lewis. During the fabrication process the MDC electrode surfaces will be treated at Lewis by an in-house-developed process to suppress secondary electron emission.

Preliminary results obtained halfway through the program are very encouraging. A TWT has been built that demonstrates the required 7 W of output power with a dc input power of 23.6 W. This TWT does not yet include an MDC and does not have the final design of the DVT, both of which are projected to raise the efficiency of the final version of the TWTA beyond the very ambitious project goals.

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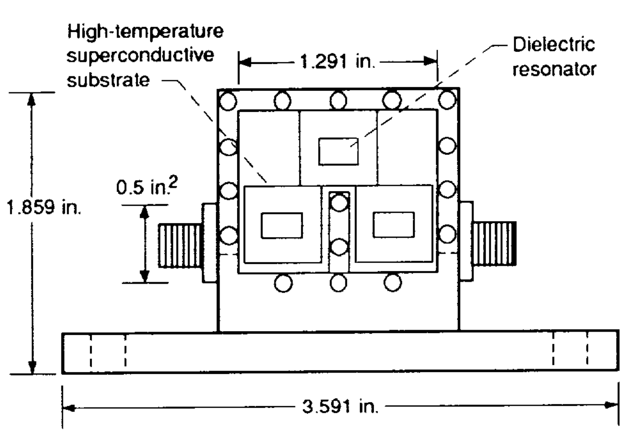
High-Temperature Superconductivity Applied to Microwave Electronics

During 1990, NASA Lewis continued to pursue the application of high-temperature superconductors, discovered in 1987, to microwave electronics. Although superconductors display a finite electrical resistance to the passage of microwave signals (in contrast to their behavior with dc signals), losses are still smaller than those experienced with normal metal circuits, at least to frequencies of nearly 100 GHz. Consequently, the potential exists to fabricate enhanced-performance microwave circuits, provided that the problems of materials, fabrication, and testing techniques can be overcome.

Working in close cooperation with The Ohio State University, Oberlin College, The University of Cincinnati, and The University of Nebraska, NASA Lewis has developed several techniques for depositing superconducting films on substrates that have useful microwave properties. The most useful of these materials appears to be yttrium-boron-carbon-oxygen (YBCO) films deposited by laser ablation on lanthanum aluminate. This particular process, was developed at NASA Lewis. It uses a high-powered pulsed laser to vaporize a bulk superconducting target, producing a plasma that then deposits on a substrate which has been heated to approximately 600 °C. Carried out in an atmosphere of low-pressure oxygen, the process consistently produces high-quality films with critical temperatures near 90 K.



Three-pole dielectric resonator filter.

In the last year NASA Lewis participated in the development of an experimental package to be flown as part of a superconducting space experiment sponsored by the Naval Research Laboratory (NRL). NASA Lewis has provided superconducting films for use in a three-pole dielectric resonator filter, designed and assembled by Ford Aerospace. To date, five filters have been supplied to NRL, where they will undergo further evaluation in preparation for an anticipated launch in late 1992.

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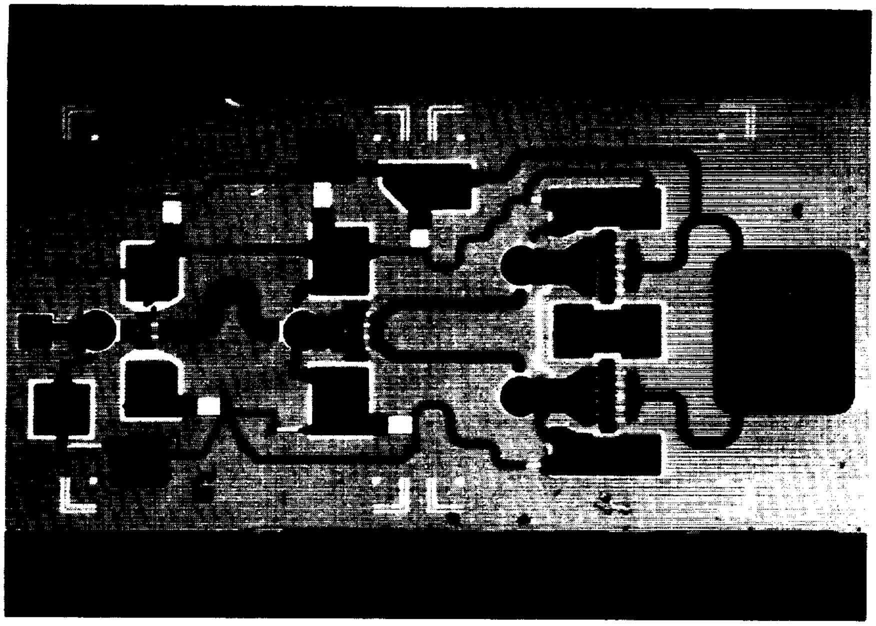
High-Power Monolithic Microwave Integrated-Circuit Amplifiers Developed

In 1990, NASA Lewis, under a contract with Texas Instruments, developed two monolithic microwave integrated-circuit (MMIC) power amplifiers that give record performance with respect to power output, efficiency, and gain. The chips are based on new concepts in materials, using conducting layers of indium gallium arsenide (InGaAs) to provide ultrahigh electron mobility and high peak electron velocities. At this frequency they have potential application in electronically steerable antennas for the return of data from deep space missions. Such an antenna would permit a spacecraft to keep a very narrow beam accurately focused on the Earth, without mechanically reorienting the spacecraft or its antennas.

The work has produced two chips, a high-gain, three-stage, 390-mW chip and a high-power (710 mW), one-stage chip. Both have efficiencies of 25 percent. Forty of the chips have been delivered to NASA's Jet Propulsion Laboratory, and an additional 70 have been ordered by JPL under a separate procurement. JPL will evaluate the chips in a breadboard version of an electronically steerable antenna.

The program is ongoing and has as a goal the production of a set of even higher performance amplifiers with power outputs up to 1 W (35 percent efficiency) and efficiencies as high as 50 percent (250-mW power).



Three-stage, 32-GHz, 390-mW MMIC chip.

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Multichannel Demultiplexer/Demodulator Will Improve Commercial Satellites

Advanced digital and optical technologies are being applied to the development of a service-enabling component for future commercial satellites. The multichannel demultiplexer/ demodulator (MCDD) may enable a new class of personal, interactive, video communications services via satellite. An MCDD allows hundreds to thousands of frequency-division multiple access (FDMA) signals to be processed simultaneously onboard the satellite for eventual routing to the appropriate user back on the ground. The FDMA technique requires significantly lower transmitter power, and therefore smaller antenna size and lower ground terminal cost, than comparable time-division multiple access (TDMA) techniques.

Two contracts were awarded in 1990 for developing proof-of-concept models of the MCDD function. Under NAS3-25866 TRW's Space Electronics Division in Redondo Beach, California, will be developing an MCDD hardware model based on a time-domain fast Fourier transform (FFT) implementation. Their digital implementation offers benefits of smaller size, smaller mass, and lower power consumption and superior functional performance than other analog techniques. TRW's MCDD consists of two cascaded channel demultiplexers followed by a time-shared demodulator. This hierarchical approach allows a single composite input signal to be demultiplexed into multiple wideband data channels (2.048 Mbps each). Each of these can be demodulated by the time-shared demodulator or demultiplexed further into thirty-two 64-kbps data streams before demodulation. The contract will be completed in late 1992. The technical monitor for this contract is James M. Budinger.

Under NAS3-25865 Westinghouse Electronics Systems Group in Baltimore, Maryland, is producing an MCDD that uses optical Bragg cells to convert signal modulation by physical

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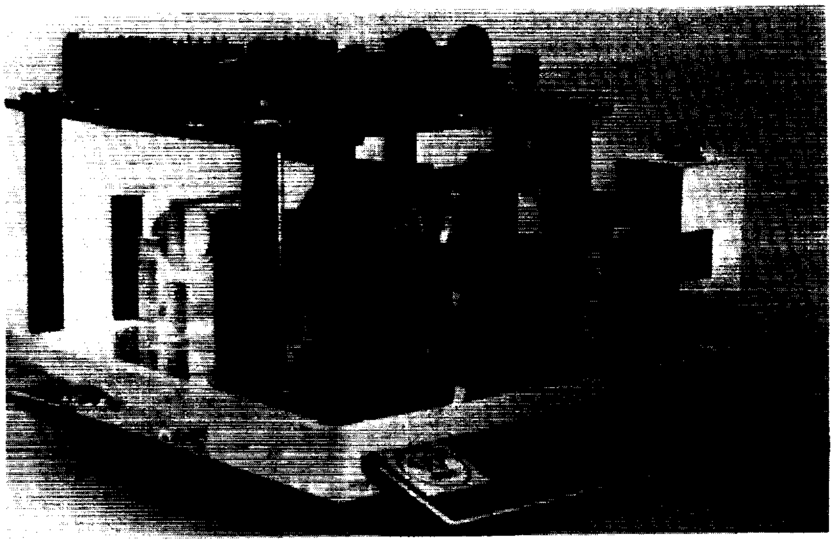

Time-integrating correlator.

displacement of a laser beam. Coupled with a reference carrier in a heterodyne configuration, an array of integrated photodetectors and demodulators processes individual wideband or narrowband channels independently. The optical approach offers advantages of passive components, simple redundancy, and physically compact packaging. The contract will be completed in late 1991. The technical contact for this contract is William D. Ivancic.

Lewis contacts: James M. Budinger, (216) 433-3496; and William D. Ivancic, (216) 433-3494
Headquarters program office: OSSA

Hi-LITE Project Makes Progress

For several years NASA Goddard Space Flight Center has conducted an Optical Communications Program to demonstrate the potential of using laser beams to communicate between Earth-orbiting satellites. The lasers can be turned on and off several hundred million times each second, enabling very high-data-rate communications. Unlike fiber optics used by the telephone system on Earth, free-space laser communications require no cable to carry the signal over tens of thousands of miles from source to destination. The problem is recovering the information carried by the signal correctly after its long journey. Through a "direct detection" process Goddard converts the extremely faint optical signal energy into an electrical signal. NASA Lewis is responsible for developing the electronics used to extract the information from the weak and distorted pulses so recovered.

Early in 1990 the High-speed Laser Integrated Terminal Electronics (Hi-LITE) Project was established to design and develop two 650-megabit-per-second (Mbps) modems for use in the flight system development and demonstration (FSDD) test bed of NASA Goddard Space Flight Center's Optical Communications Program. In addition to the communications electronics subsystem the Hi-LITE team at NASA Lewis is responsible for the ground support equipment and controlling software, test data sources at 325 and 650 Mbps, digitized high-resolution video equipment, optical link effects simulation, and computer control of the experiment and data collection.

Two versions of the 650-Mbps quadrature pulse-position modulation (QPPM) modem are under development. The first one, designed and fabricated completely in house, uses discrete gallium arsenide digital logic and analog integrated circuits to demonstrate functional performance. The second one, designed in house but fabricated under contract, will be implemented as a semicustom digital chip and an analog hybrid module to demonstrate flight qualifiability. The two modems will enable demonstration of duplex communications through a free-space laser link. The Hi-LITE team completed conceptual and preliminary design reviews in May and November 1990, respectively. Integration into the FSDD test bed at Goddard is scheduled for January 1993.

A flight-like configuration of the optical transceiver assembly might consist of the laser transmitters, the telescope, and the optical detectors, and the electronics assembly would consist of modules for pointing, tracking, control, and communications.

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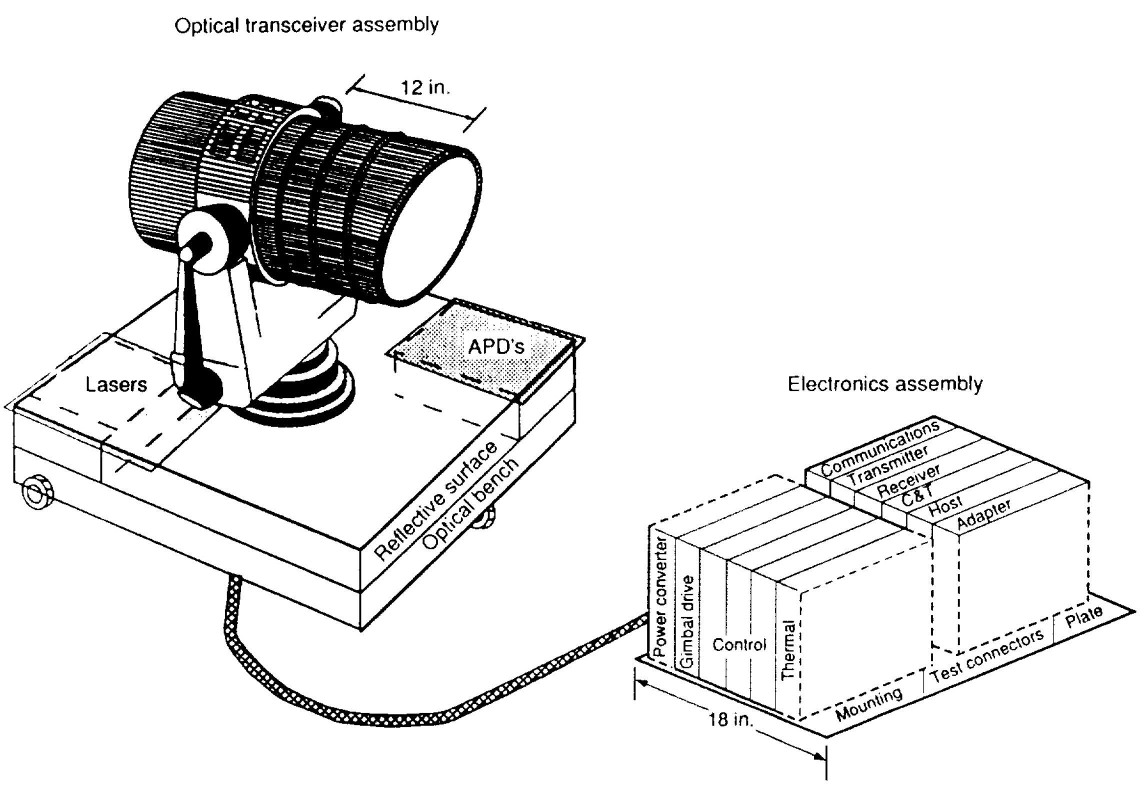
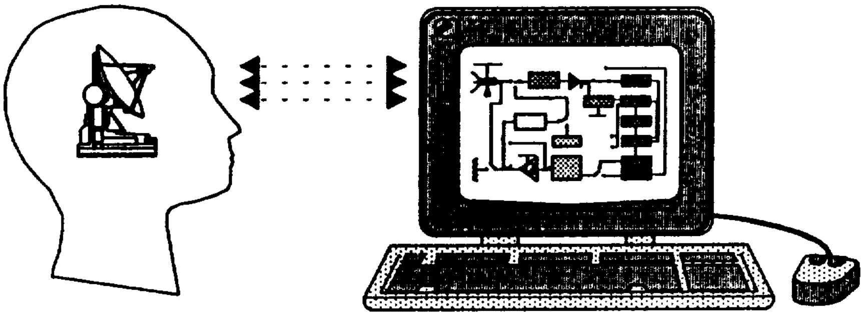


Flight configuration of optical transceiver assembly.

Artificial Intelligence Will Enhance Satellite Ground Terminals

Four artificial intelligence (AI) techniques are being used to enhance the technology for space communications ground terminals. Over the last several years some very useful applications have arisen as a result of AI research. For example, expert systems have become well known for capturing human expert knowledge and making it available to others in such fields as diagnostics, intelligent assistants, and intelligent tutoring systems. More recently, as a result of continuing AI research and the availability of more powerful computers, a field known as multimedia documentation has emerged. All four of these AI techniques are being used at NASA Lewis within the Systems Integration, Test, and Evaluation (SITE) Facility for the Advanced Communications Technology Satellite (ACTS) Project. In short, the SITE facility provides laboratory support for the ACTS project.

These AI techniques are being incorporated into an advanced ground terminal design to facilitate the maintenance, use, training, and



Artificial intelligence.

documentation of ground terminal hardware and software systems. Traditionally, the same requirements have been provided by paper manuals, user guides, classroom sessions, blueprints, and other hard-copy material. The AI applications of this project allow these requirements to be entirely computerized. Additionally, the computer gives us the ability to include some functionality that is not possible with traditional methods.

The diagnostic expert system allows a person to intelligently detect and isolate unacceptable conditions and take action to resolve problems. The expert system intelligently guides a person through troubleshooting procedures that replicate an expert's approach to isolating causes of faults within the advanced ground terminal system.

Setup and data acquisition procedures can be very tedious and time consuming with the advanced ground terminal. The intelligent assistant is in the form of a friendly interface that shields an operator from the complexity of the advanced ground terminal system. It also alerts an operator to abnormal or erroneous conditions and assists the oper-ator to resolve the condition.

Computer-assisted instruction (CAI) has become a widely used training method. CAI is conducted by a computer program that takes a user through a fixed set of lesson plans. The advent of artificial intelligence technology and advances in cognitive psychology have given rise to intelligent tutoring systems (ITS). ITS expands on the CAI technology by determining what concepts the student needs to learn from the student's current level of knowledge. The student is then taken through tests to find out which concepts are lacking. Depending on the needs of each student, the ITS determines what the student needs to be taught. In addition, an ITS can sense how well a student is progressing with lessons and present more or less detail to the student as appropriate.

The multimedia documentation effort extends well beyond conventional documentation techniques by combining text, graphics, voice, and video within the computer. Dynamic links are available to allow easy navigation within the system for ready access to documentation information. Multimedia technology allows one to view graphic schematic images and to request written specifications of components, detailed images of subsystems, connectivity information between subsystems, and assembly diagrams.

Most of the work on this project has been accomplished in house, although a portion was performed under a grant with The University of Akron in Akron, Ohio. Demonstrable prototype systems have been developed for all four artificial intelligence techniques. This ongoing work is directed at extending each prototype system to operational completion.

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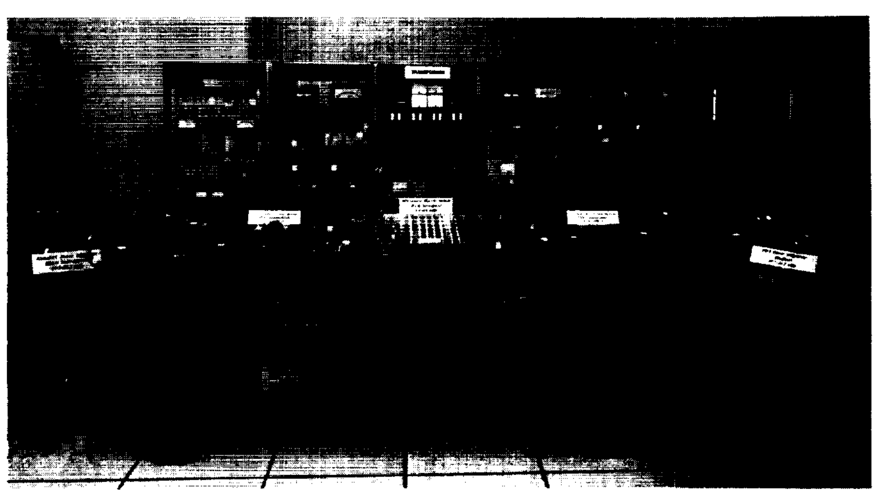
Systems Integration, Test, and Evaluation Project Supports ACTS

The Systems Integration, Test, and Evaluation Project uses a unique, laboratory-based test facility to investigate advanced space communications technology. The facility includes the satellite portion of a space communications channel, as well as several ground terminals, combined into a communications network under computer control. The test facility, designed and built at NASA Lewis, consists of real satellite hardware combined with high-data-rate digital ground terminals to present an accurate model of a satellite communications system. The test facility's flexibility allows evaluation of advanced system design concepts, component performance, hardware and software, and networking and control technology. System experiments, such as performance degradation due to interference or signal attenuation due to rain, are also performed. Major components of the facility (e.g., high-power amplifiers and high-data-rate modems) are the result of NASA-directed technology development contracts. The digital ground terminals and transponder integration are entirely in-house efforts.

The first phase of the SITE project established a complete simulated satellite link. An extensive test program has evaluated the performance of numerous proof-of-concept components in a real digital data environment. The results of these tests have been reported at seven conferences and in 17 publications. The second phase of the project, now under way, simulates a three-terminal, satellite-switched, time-division multiple access system, with network operations, ground terminal synchronization, and video transmission as some of the parameters under test. The system also includes a radiative (20 and 30 GHz) link to a remote terminal. Plans are also under way to expand the SITE system simulator to include millimeter-wave and optical technology.

In addition to the general communications research capabilities of SITE, the project also includes several specific thrusts that support current and future NASA programs. In support of the ACTS program the SITE project provides experimental data that assist the ACTS flight and ground systems. The high-burst-rate link evaluation ground terminal development also relies heavily on SITE facilities and expertise. Another major SITE effort is the development of low-cost ground terminals for satellite communications applications.

In the development of low-cost ground terminal systems and in support of SITE digital electronic systems, application-specific, integrated-circuit (ASIC) facilities have been implemented that will provide the state-of-the-art, computer-assisted-design (CAD) features required in developing high-performance digital systems. The ASIC design capabilities are unique at Lewis and offer the increased



SITE facility.

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performance and reliability in digital electronics necessary for the development of future space communications, power, and propulsion applications. The development of advanced high-frequency analog circuits has also been enhanced with a state-of-the-art CAD facility. Coupled with the Space Electronics Division's circuit fabrication expertise and the ASIC capabilities, the SITE project now has considerable design facilities to be applied to the development of future space communications systems.

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Headquarters program office: OSSA

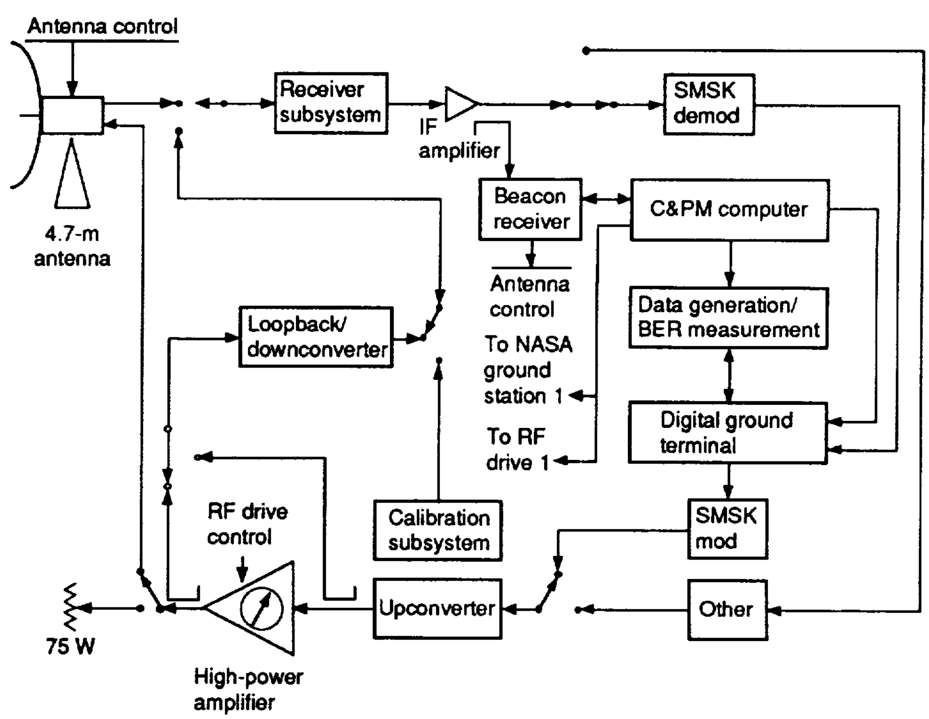
High-Burst-Rate Link Evaluation Terminal Being Assembled

In support of the Advanced Communications Technology Satellite (ACTS) Project, NASA Lewis is developing the high-burst-rate link evaluation terminal. This versatile and adaptable experimental test facility will support various ACTS technology experiments, such as the characterization of the multibeam communications package on the satellite and adaptive uplink and downlink radiofrequency power augmentation.

The terminal will operate at burst rates of 110 and 220 Mbps. Data rates are discretely variable from 1.25 to 200 Mbps. The digital subsystem has been designed and built at Lewis. Uplink power will be provided by a 30-GHz traveling-wave-tube amplifier that delivers 60 W of saturated radiofrequency power. The receiver subsystem will use a low-noise receiver built by Harris Corporation for the ACTS Proof-of-Concept Program. Also utilized from that program will be a 4.7-m-diameter antenna built by Scientific Atlanta. An upconverter subsystem is being built at Lewis, as are the loopback and calibration subsystems. The loopback subsystem permits an end-to-end check of the terminal without open-loop operation. The calibration subsystem provides reference signals for calibrating the beacon receiver.

Final assembly of the terminal has begun. System level testing is scheduled for March 1991. The terminal is on schedule for testing with the ACTS spacecraft in the fall of 1991.

Lewis contact: Gerald J. Chomos, (216) 433-3485
Headquarters program office: OSSA



Schematic of high-burst-rate link evaluation terminal.

Contract Awarded for 30-GHz Ground Terminal Power Amplifier

NASA Lewis is working to develop a solid-state power amplifier that can be produced at significantly less cost than a traveling-wave tube and to make this technology available to U.S. manufacturers of commercial ground terminals.

On October 19, 1990, Avantek Incorporated of Santa Clara, California, was awarded a contract for the design, fabrication, and test of a proof-of-concept model of a 30-GHz power amplifier. The contract period of performance is 36 months. The first 2 years of the effort will be devoted to developing the requisite 30-GHz field-effect transistors. The final year will be used for integrating the devices into a power amplifier.

The salient features of the amplifier are a power output of 10 W, a frequency of 29 to 30 GHz, an efficiency greater than 30 percent, and gain of 40 dB.

The development of a low-cost 30-GHz ground terminal power amplifier will provide NASA with another key component required for the broader objective of developing low-cost ground terminals.

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Advances Made in Monolithic Gallium Arsenide Switch Matrix

Over the past several years NASA Lewis has sponsored the development of microwave switch matrices for use in satellite-switched, time-division multiple access communications systems. Present designs rely on advanced hybrid microwave integrated circuits to build a switch matrix such as the type to be flown on NASA's Advanced Communications Technology Satellite (ACTS). As part of an ongoing contract with Microwave Monolithics, Inc., the development of the next generation of switch matrix technology is now under way.
A 6×6 (six input by six output) microwave crossbar switch matrix operating over 3 to 6 GHz is being fabricated from gallium arsenide (GaAs) monolithic microwave integrated circuits (MMIC's). The primary function of the MMIC GaAs switch matrix is to perform high-speed switching and routing of multiple microwave signals without interference between channels. A significant feature of the MMIC approach is the large-scale integration of many GaAs field-effect transistor switches in close proximity on a single chip while keeping isolation high for minimal channel-to-channel crosstalk. Tests performed on single crosspoints have resulted in isolation performance better than 60 dB. The addition of fixed-gain amplifiers around the periphery of the switch matrix chip will yield a device with an overall insertion loss of 0 dB. A modular design concept combined with a unique packaging approach will allow for the cascading of these zero-insertion-loss switch submodules into larger MMIC switch matrices with little or no performance degradation.

The monolithic implementation of the microwave switch matrix is attractive for communications satellite systems primarily because of its low power consumption, reduced size and weight, and potentially lower costs. High reliability is obtainable with the fully monolithic very-large-scale-integration (VLSI) switching MMIC. The potential exists for affordable manufacturing of large switch matrices (size 96×96 or beyond) for future switching applications.

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Space Flight Systems

Cryogenic Fluids Technology

No-Vent Fill Technology Makes Strides

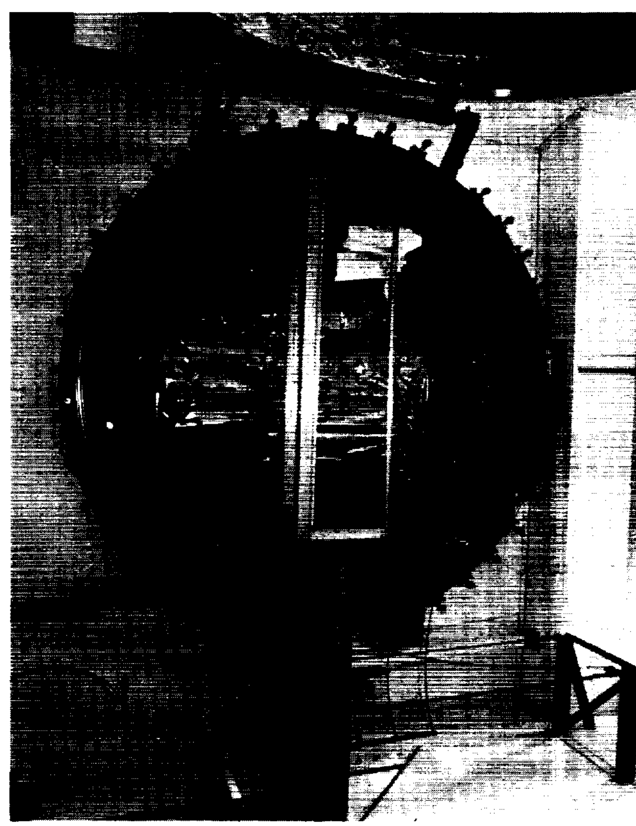
Currently, all spacecraft must leave Earth loaded with enough fuel for the whole mission. To be cost effective, future spacecraft must be reusable and refillable with cryogenic liquids like liquid hydrogen (LH_2). The transfer of cryogenic liquids in the low-gravity environment of space will require a new level of technology. Engineers, scientists, and technicians in NASA Lewis' Cryogenic Fluids Technology Office (CFTO) are implementing no-vent-fill ground test programs and analytical modeling efforts to develop practical methods for the on-orbit transfer of cryogenic liquids. During 1990, the CFTO (including support service contractors) made strides toward a technology goal of being able to complete an on-orbit cryogenic liquid transfer to a prototype spacecraft, filling it up to 95 percent full while keeping receiver tank pressures low.

In 1990, the CFTO completed several successful series of 1-g (Earth normal gravity) no-vent fill tests. At Lewis' Cryogenic Components Laboratory (CCL), no-vent fills were conducted with LH_2 and liquid nitrogen (LN_2) in 5-ft^3 and 1.2-ft^3 vacuum-jacketed receiver tanks (dewars). These tests demonstrated an ability to perform no-vent fills over a broad range of cryogen initial conditions and with several different techniques of injecting the cryogenic liquid into the dewars. At Lewis' Plum Brook Station, no-vent fills were completed at K-Site facility on a large (175 ft^3) flight-weight receiver tank. This 1990 test series represents the first ever successful no-vent fill with LH_2 on a tank built to the lightweight, high-performance standards required for actual spacecraft propulsion systems. No-vent fill testing at both CCL and K-Site will continue to explore the requirements of successful and efficient no-vent fills.

To enhance future technology research, CFTO personnel were busy in 1990 developing computer models that can simulate a wide range of no-vent fill conditions and hardware. The results of such analytical modeling must be validated against actual, physical test data. A validation of analytical modeling efforts against test data from CCL no-vent fill testing was published in reference 1.

The two-pronged approach to developing no-vent fill technology in the CFTO will continue through at least 1993. New no-vent-fill test series are planned for the CCL and K-Site. The effort to validate analytical models will continue as more and more physical test data can be compared with predictions made by the computer models.

As NASA reaches back to the Moon and then on to Mars, many mission scenarios call for the ability to transfer cryogenic liquids on orbit and even in transit. The focused technology program for no-vent fill being



K-Site facility.

conducted by the CFTO is part of the Lewis effort to aid in NASA's return to the Moon and journey beyond.

Reference

1. Chato, D.; Moran, M.; and Nyland, T.: Initial Experimentation of the Nonvented Fill of a 0.14 m^3 (5 ft^3) Dewar With Nitrogen and Hydrogen. AIAA Paper 90-1681, June 1990. (Also NASA TM-103155.)

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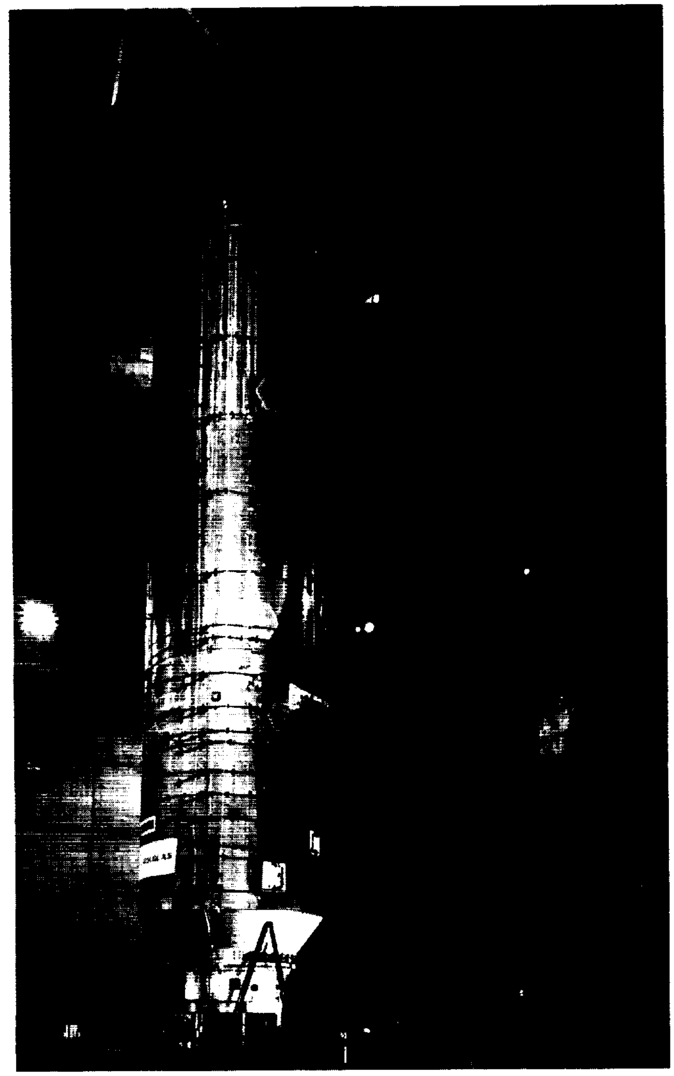
Launch Vehicles

Payload Fairing Separation Tests for Titan IV and Atlas I Launch Vehicles Are a Success



Titan fairing in vacuum chamber.

A Titan IV payload fairing and an Atlas I payload fairing were both successfully jettison tested in the world's largest vacuum chamber located at NASA Lewis Research Center's Plum Brook Station near Sandusky, Ohio. A payload fairing (PLF) is an aerodynamically shaped shroud that mounts on top of the launch vehicle's upper stage to protect the payload (satellite) from atmospheric friction and contamination during its launch into space. When the launch vehicle rises above the Earth's atmosphere, the payload fairing is no longer required for protection, and so it is separated (jettisoned) from the launch vehicle to reduce weight. The tests performed at Plum Brook verified the payload fairing separation in a simulated space environment on the ground.

The Titan fairing measures 86 ft long by 16.7 ft in diameter and has internal payload space dimensions approximately those of the space shuttle orbiter bay. The fairing weighs more than 10,000 lb. Successful completion of the separation tests at Plum Brook qualified the 86-ft fairing for service on the Titan IV. The Air Force has scheduled initial launch capability with the fairing for the second half of 1991.

For this test, which was conducted in late October, the fairing was loaded with weights to simulate an actual payload. Environmental conditions approximated the 5×10^{-4} torr pressures found at 380,000 ft. The jettison was completed in less than 500 msec, and data from accelerometers, pressure transducers, strain gages, and other measuring devices were collected from more than 600 data channels.

The Atlas I fairing test is similar to the Titan test, but the fairing is smaller, measuring about 40 ft in length by 14 ft in diameter. Previous Atlas payload fairings had diameters of only 10 ft and were not large enough for the bigger satellites of the 1990's.

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Space Experiments

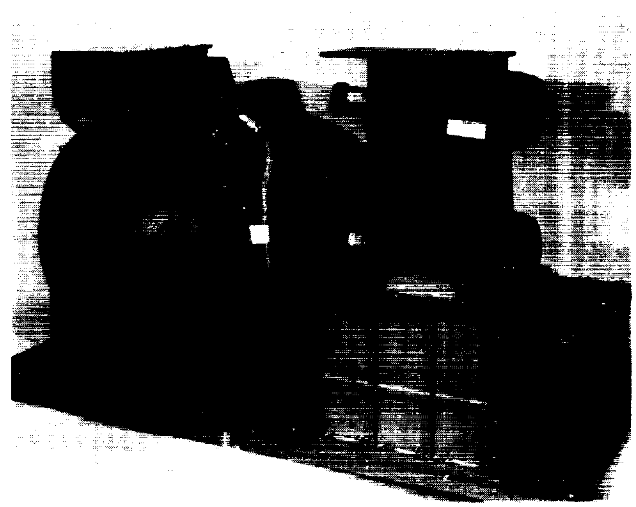
Solid Surface Combustion Experiment Flies

The Solid Surface Combustion Experiment (SSCE) was flown for the first time aboard the STS-41 shuttle mission on October 6-10, 1990. The SSCE is the first combustion experiment to fly in the shuttle and first in the NASA spaceflight program since Skylab. It was conceived by Professor Robert A. Altenkirch, Dean of Engineering at Mississippi State University, and built by NASA Lewis. The project is supported by the NASA Headquarters Microgravity Sciences and Applications Division of OSSA.

The purpose of the SSCE is to study the physical and chemical mechanisms of flame spread over solid fuels in the absence of gravity-driven buoyant or externally imposed airflows. Because the controlling mechanisms of flame spread are different in low gravity and normal gravity, the results of the SSCE experiment have a practical application in the evaluation of spacecraft fire hazards. In this first flight the fuel sample—ashless filter paper instrumented with three thermocouples—was mounted in a sealed chamber filled with a 1:1 mixture of oxygen and nitrogen at a pressure of 1.5 atm and was ignited with an incandescent wire. Two 16-mm motion picture cameras photographed the experiment from perpendicular perspectives, and thermocouple temperature and chamber pressure measurements were recorded with a digital data acquisition and control system. The SSCE is self-contained and battery operated and can be flown either on the shuttle middeck or in the Spacelab module. For safety and simplicity, only one specimen is burnt in the test chamber during each mission. Reference 1 provides more information concerning the hardware configuration.

The SSCE payload was designed and built at NASA Lewis. Design, engineering, qualification testing, scientific support, and flight operations functions were performed by the Lewis Space Experiments Division. The hardware was fabricated and assembled by the Lewis Technical Services Directorate. The SSCE project was supported in some way by nearly every major element of the Lewis organizational structure.

The SSCE hardware was activated and performed without incident during the second day of the STS-41 mission; the test specimen was ignited and the transducer and imaging data were recorded precisely as designed. The shuttle crew spontaneously attached a video camera to the experiment for a welcome early downlinking of the preliminary results. The crew verbally reported evidence of a flame sustained for 70 sec. The motion picture films showed that the initial spreading of the flame occurred during the first 23 to 27 sec and that fuel not consumed during the spreading burned sporadically thereafter. Preliminary assessments of the thermocouple data indicate that the profile shapes are consistent with theoretical expectations. An integrated analysis of the temperature, pressure, and imaging data has been performed and will be prepared for publication.



SSCE flight hardware for STS-41.

The principal investigator, Professor Altenkirch, has developed a numerical simulation (see ref. 2) of the flame spreading process from first principles (of fluid mechanics, heat transfer, and reaction kinetics). The spread rates, the flame shape, and the thermodynamic data from the SSCE flight are being compared directly with the results of the computational model. The flight temperature data indicate that the solid-phase kinetics parameters commonly used for normal-gravity flame spread modeling do not reproduce the flame structure observed. This discovery will be explored during later flights of the SSCE.

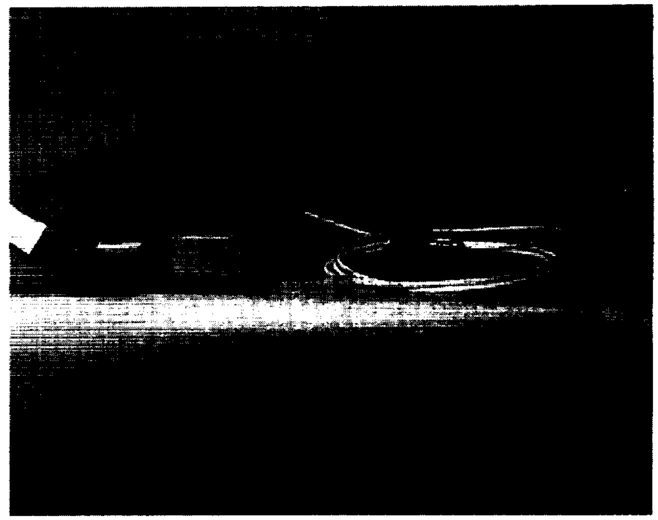
The SSCE project is currently scheduled for eight flights. Ashless filter paper will be tested on the next four flights in different mixtures of oxygen and nitrogen at different pressures; the final three tests will use PMMA (polymethylmethacrylate). The SSCE is currently manifested aboard the SLS–1 Spacelab mission (May 1991), in the middeck on STS–43 (June 1991), and again aboard the USML–1 Spacelab mission (March 1992).

References

1. Vento, D.M.; et al.: The Solid Surface Combustion Space Shuttle Experiment Hardware Description and Ground-Based Test Results. AIAA Paper 89–0503, Jan. 1989.

2. Bhattacharjee, S.; and Altenkirch, R.A.: Radiatively Controlled Flame Spread. Twenty-Third Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA, 1990.

Lewis contacts: Ralph Zavesky, (216) 433–2838; and Kurt Sacksteder, (216) 433–2857
Headquarters program office: OSSA



SAMS main unit.

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Space Acceleration Measurement System Delivered

Many experiments are flown on the shuttle to utilize the reduced levels of gravity during the orbital operations. The actual levels of acceleration and vibration experienced by the experiments quite often need to be measured to enhance the analysis of the experimental results. The Space Acceleration Measurement System (SAMS) Project has designed and fabricated an instrument to measure acceleration at or near experiments on the shuttle. The data are provided to the experimenter after the mission or, in some cases, in near real time at a payload operation center. A data base of this acceleration environment will also be developed and maintained to facilitate future analyses and predictions of expected environments. The SAMS project in 1990 fabricated, tested, and delivered three flight units to the NASA Kennedy Space Center (KSC) for integration into three shuttle missions. A fourth unit was also fabricated and tested in 1990 for delivery to KSC early in 1991. The final design was completed in 1990 for a second configuration, of which two additional flight units will be fabricated. These six flight units will be flown on numerous shuttle missions in the coming years, averaging about three to four flights per year.

The SAMS project has developed a general-purpose instrument for measuring and recording the very low levels of acceleration (e.g., from gravity, vibrations, and thrusters) experienced onboard the shuttle, both for documenting what the experiments experience and for helping to predict the expected acceleration environment prior to missions. The SAMS instrument is flexible in several ways to meet the needs of various types of experiments (e.g., fluid physics, crystal growth, and combustion) that will be located in the shuttle middeck and cargo bay, the Spacelab module, and the Spacehab module. Each SAMS main unit can have up to three remotely positioned three-axis sensor heads that are mounted in, on, or near the experiment apparatus and connected to the main unit by cables. Each of the three sensor heads may be independently set to one of six low-pass-filter frequencies depending on the requirements of the experiment. One style of main unit is configured for installation in the habitable areas of the shuttle (the middeck, the Spacelab module, and the Spacehab module). The other style of main unit is designed for installation in the shuttle cargo bay.

Data are acquired and stored continuously during a typical mission of 7 to 13 days. Because gigabytes of data may be generated by a typical mission, a high-density data storage medium is needed. The data recording is performed by optical disks that have a capacity of 400 megabytes. When filled with data, these disks can be changed by the crew, provided that the SAMS is installed in the middeck, Spacelab, or Spacehab. Additional disk drives and data downlinking are used in the cargo bay configuration to increase the data capacity for the mission, since crew disk changeout is not possible.

SAMS is expected to support approximately three or four flights per year. This flight rate is expected to continue until Space Station *Freedom* is operational.

During 1990 the SAMS project has delivered three flight-ready units to KSC for integration into the first Spacelab Life Sciences mission, the first International Microgravity Laboratory mission and the Spacelab J mission. The fourth flight unit was fabricated and assembled in preparation for the first United States Microgravity Laboratory mission and has nearly completed its testing program. This unit will be delivered to KSC early in 1991. Also during 1990 the design for the cargo bay configuration was carried forth to the final design stage. Mission integration activities for eight missions have also been conducted throughout 1990.

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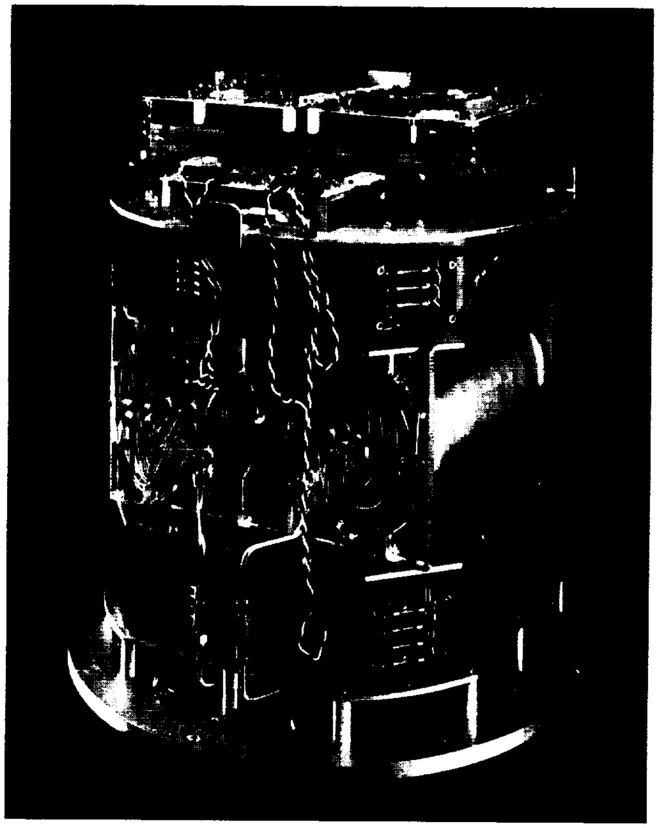
Headquarters program office: OSSA

GaAs Crystal Growth Experiment Scheduled for Flight

Gallium arsenide (GaAs) substrates and devices are considered a leading contender for a new generation of electronics technology offering greater speed and durability than existing silicon-based systems. High-quality crystals of GaAs are difficult to produce and the commercial crystal growth of this material is of significant interest. The effect of gravity-induced, buoyancy-driven convection on the types and distribution of defects in GaAs is the focus of a study being conducted by GTE Laboratories, Inc., of Waltham, Massachusetts. The work is cost shared by GTE, the Air Force Materials Laboratory, and the Microgravity Science and Applications Division of OSSA. The Space Experiments Division of NASA Lewis manages the project. The Lewis Materials Division has implemented numerical modeling of the furnace and fluid flow and the Lewis Space Electronics Division will characterize selected samples from the study.

The study, as proposed by GTE (the principal investigator is Dr. Brian Ditchek), consists of a systematic investigation of the effect of buoyancy-driven fluid flow on GaAs crystal growth. It will include GaAs crystal growth in the microgravity environment aboard the space shuttle. The program involves a comparative study of crystal growth under a variety of Earth-based conditions with variable orientation (to change the direction of the gravity vector) and applied magnetic field (to partially damp flow) in addition to the microgravity growth. Earth-based growth will be performed under stabilizing as well as destabilizing temperature gradients. The



Self-contained dual furnace payload for GaAs crystal growth experiment.

boules grown in space and on Earth will be fully characterized to correlate the degree of convection with the distribution of impurities. Both macro- and microsegregation of dopant will be determined.

Design and fabrication of the experimental hardware was fully implemented by the GTE team led by Alfred Bellows. The space growth experiment will be flown in a self-contained payload container through NASA's Get Away Special Program. The advantages of using the GAS program are the simplicity of manifesting the payload aboard the shuttle, the frequent flight opportunities, the quick turnaround necessary for iterative experiments, and the low cost. The payload with its large alkaline battery power source will include two redundant experimental systems each with a separate, well-insulated growth furnace. The samples are approximately 1 in. in diameter and 4 in. long. Each sequentially scheduled growth experiment will require approximately 8 hr to complete, and collected data will include measurements of acceleration, selected temperatures, and furnace power. The use of the specially designed growth ampoule and furnace system for both space- and Earth-based growth experiments will lend validity to the comparative studies and simplify the numerical modeling of the furnace and ampoule.

Development and testing of the flight hardware has been completed, and the flight of the payload is scheduled for May 1991.

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Critical Fluid Light-Scattering Experiment Makes Progress

The Critical Fluid Light Scattering Experiment (dubbed Zeno by the principal investigator in honor of the ancient Greek philosopher noted for descriptions of paradoxes of infinity) will use dynamic light-scattering spectroscopy and correlation analysis to study the density fluctuations of xenon at temperatures very near (within 100 microkelvin) the critical temperature for the vapor/liquid phase transition of this ideal fluid. These data will provide a test of theories describing such phase changes in realms that are theoretically very interesting (strong divergences of dynamic properties such as compressibility, thermal conductivity, heat capacity, and viscosity are predicted) but inadequately tested to date at the temperatures of most interest. Such measurements are severely limited on Earth by the large density gradients created by normal gravity acting on the fluid as the compressibility of the sample increases (diverges) near the critical temperature. The ultimate impact of such theories will be far-reaching because the theories provide "universal" descriptions of many transitions

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such as ferromagnetization, superconductivity, and binary fluid miscibility limits.

The principal investigator is Prof. Robert W. Gammon of the Institute for Physical Science and Technology at The University of Maryland, College Park. Prof. Gammon has assembled a team of 10 at the university that includes graduate research assistants, postdoctoral scientists, project engineers, and program/contract administrators. This team has the responsibility, under the NASA contract, for both definition of the science requirements and development of the flight instrument. The flight hardware engineering, fabrication, integration, and testing are subcontracted to the Ball Aerospace Group of Boulder, Colorado.

During 1990 the instrument design was near completion and the engineering hardware was built. Significant progress was made in fabrication and testing of the electronics, including the microkelvin temperature control and measurement systems and alignment of the precision optical system for the light-scattering measurements. Completion of the detailed design, qualification of the instrument, and fabrication of flight hardware are scheduled for the coming year. Laboratory observations of the approach to equilibrium of critical xenon following small temperature pulses led to a series of papers (refs. 1 to 3) documenting the data and analyzing the observations. These studies have provided a better rationale for the flight experiment timeline.

The flight instrument is currently on the manifest for STS-67 (August 1993) as part of the USMP-2.

References

1. Onuki, A.; Hao, H.; and Ferrell, R.A.: Fast Adiabatic Equilibration in a Single-Component Fluid Near the Liquid-Vapor Critical Point. Phys. Rev. A, vol. 41, no. 4, Feb. 15, 1990.

2. Boukari, H.; et al.: Critical Speeding Up in Pure Fluids. Phys. Rev. A, vol. 41, no. 4, Feb. 15, 1990.

3. Boukari, H.: Critical Speeding Up Observed. Phys. Rev. Lett., vol. 65, no. 21, Nov. 19, 1990.

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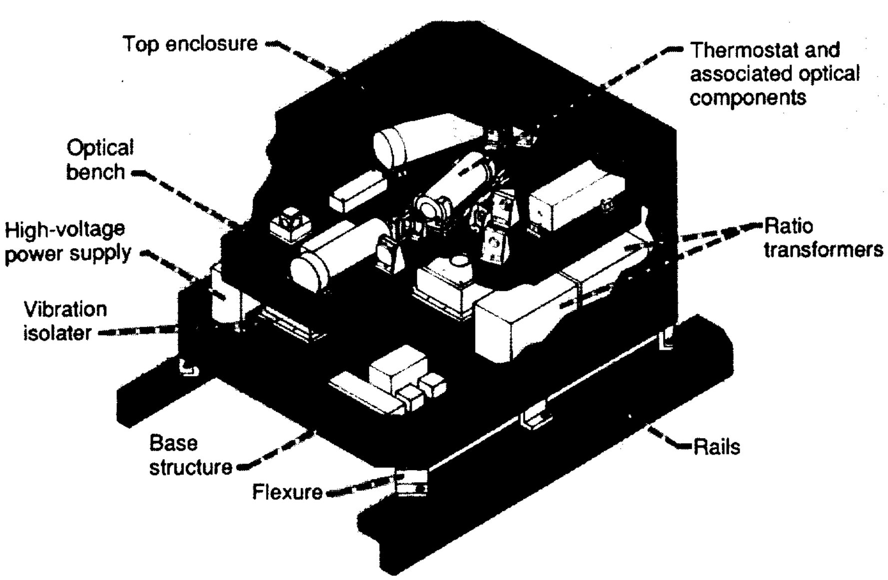


Zeno optics module showing optical bench and selected support systems.

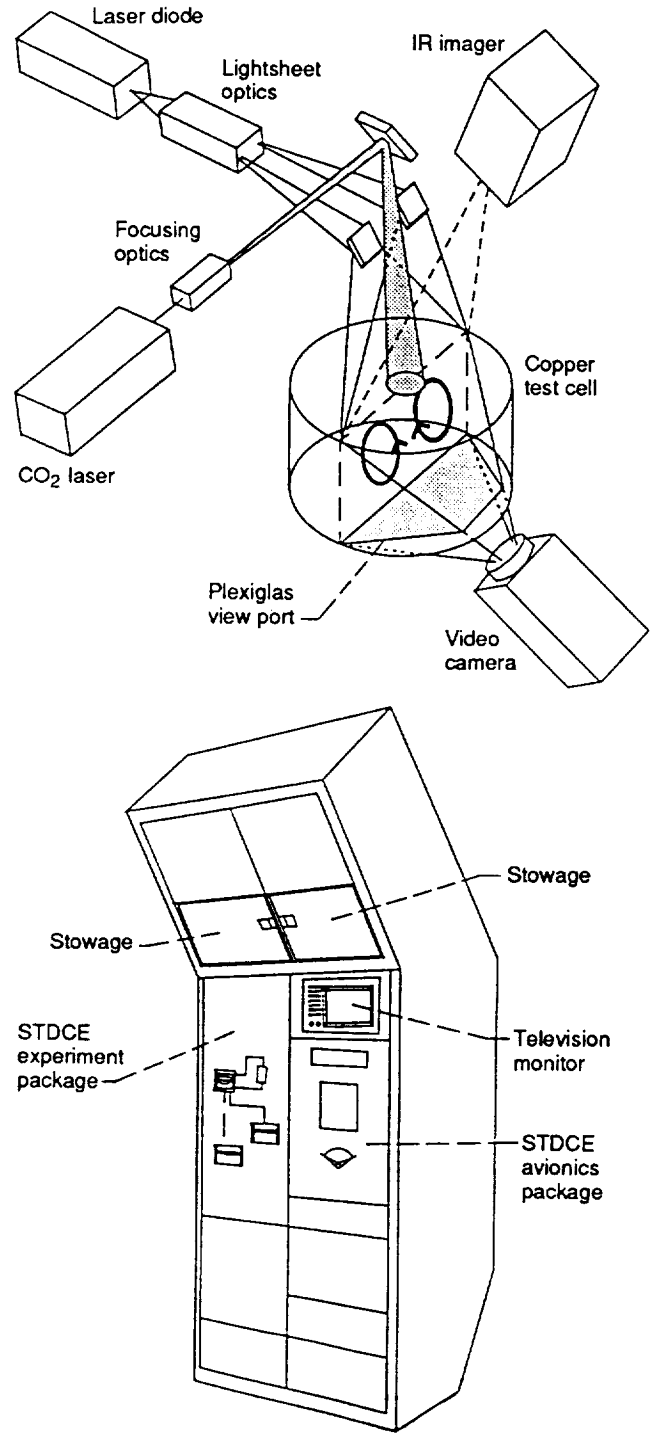
Surface-Tension-Driven Convection Experiment Nears Flight-Readiness

Materials processing that involves solidification and crystal growth is generally expected to be dramatically improved in the microgravity environment of space because natural convection and buoyancy effects are eliminated. However, convection currents due to surface tension forces are still present. These thermocapillary flows result from the fluid motions generated by the surface-tractive force that is caused by surface tension variations due to the temperature gradient along the free surface.

Changes in the nature and extent of these thermocapillary flows can cause deleterious fluid oscillations. Numerical modeling is not adequate to predict the parameters for which these oscillations occur because of an inherent coupling among the imposed thermal signature, the surface flow, and the surface deformation. In order to complete an understanding of the physical process and develop an accurate numerical model, experimental data must be obtained in an extended low-gravity environment. Therefore, the Surface-Tension-Driven Convection Experiment (STDCE) was proposed for the space shuttle.

The STDCE consists of a copper test cell, 4 in. in diameter by 2 in. deep, filled with silicone oil to provide both a flat and a curved free surface that can be centrally heated either externally by a carbon dioxide laser or internally. The cross section is illuminated by a 1-mm-thick sheet of light, which scatters from small aluminum oxide particles mixed into the oil, allowing observation of the axisymmetric flow velocities.

The design and development of the STDCE flight hardware is an in-house project at NASA Lewis. Major components were developed under contract: an infrared thermal imager for mapping the surface temperature gradients, a carbon dioxide laser for surface heating, and a laser diode system for illumination. These components were integrated with the mechanical, optical, electrical, electronic, and structural systems that were designed, fabricated, and tested at NASA Lewis.



Surface-tension-driven convection experiment in Spacelab.

The current goal is to have experiment hardware ready for shipment to the NASA Kennedy Space Center by May 1991, for integration into a double rack of the Spacelab module for the USML-1 mission in May 1992.

The USML–1 mission is managed at the NASA Marshall Space Flight Center (MSFC). The STDCE team participated in the integrated payload reviews held at the NASA Johnson Space Center in November 1990 for flight safety and at the NASA Kennedy Space Center in December 1990 for ground safety.

In October 1990 the critical design review was conducted of the design changes resulting from the extensive testing program on the engineering models of STDCE and from the fabrication of flight hardware. A major change was in the flow visualization system, where a solid-state video camera was modified in house and qualified for use in the Spacelab. The STDCE experiment and avionics packages were assembled for qualification tests. The avionics package successfully passed the simulated launch vibration tests in December, but the experiment package tests were delayed until January 1991.

In December 1990 a 1-week training session was held at NASA Lewis for the USML–1 payload crew to review the STDCE design and procedures. They practiced operations on the engineering model hardware, which eventually will be sent to the Payload Crew Training Complex at MSFC for mission simulations. Also, several STDCE team members were selected to participate at the Payload Operations Control Center at MSFC during the USML–1 mission. They will assist the principal investigator and the science team in obtaining real-time data and videotapes and interact with STDCE to change experiment parameters.

Bibliography

Kamotani, Y.; and Ostrach, S.: Design of a Thermocapillary Flow Experiment in Reduced Gravity. Thermophys. Heat Trans. vol. 1, no. 1, Jan. 1987, pp. 83–89.

Ostrach, S.: Surface Tension Gradient Induced Flows at Reduced Gravity. NASA CR–159799, 1980.

Pline, A.D.; et al.: Hardware Development for the Surface Tension Driven Convection Experiment. J. Spacecraft Rockets, vol. 27, no. 3, May–June 1989, pp. 312–317.

Pline, A.D.; and Butcher, R.L.: Spacelab Qualified Infrared Imager for Microgravity Science Applications. Thermosense XII, SPIE Proc., Vol. 1313, S.A. Semanovich, ed., SPIE, 1990, pp. 250–258.

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Apparatus Being Fabricated for Isothermal Dendritic Growth Experiment

The Isothermal Dendritic Growth Experiment (IDGE), to be conducted onboard the space shuttle beginning in 1993, will test fundamental theories that describe dendritic freezing of liquid metals on Earth. Rensselaer Polytechnic Institute scientists proposed the experiment to NASA. NASA Lewis then designed and is fabricating and testing the spaceflight apparatus.

The IDGE spaceflight apparatus will acquire data needed to correct current theories that predict metal dendrite growth kinetics during the freezing process. Experimentation on Earth has had limited success because gravity-driven convective effects cannot be separated from conductive and diffusive effects. Since steel, aluminum, and superalloys freeze dendritically, IDGE results should lead to improvement of their Earth-based production.

Three flights are planned for 1993 to 1997 on the NASA Marshall Space Flight Center-managed USMP experiment carrier. Two will involve succinonitrile (a transparent material having a crystal structure similar to iron), and one will involve pivalic acid (a transparent material having a crystal structure similar to nickel).

The unique spaceflight apparatus will automatically carry out 25 dendritic growth experiments per flight. During each experiment it will maintain growth temperatures accurately to within 0.002 kelvin, automatically detect growing dendrites by analyzing slow-scan television images, and acquire 20 dendrite photographs. In addition, slow-scan television images of growing dendrites and over 100 other data items will be continuously communicated to Earth. Should a problem arise, the apparatus can be commanded from the Payload Operations Control Center on Earth.

Fabrication of the IDGE spaceflight apparatus began in 1990 and will be completed in mid-1991.

Bibliography

Glicksman, M.E.; et al.: Isothermal Dendritic Growth—A Proposed Microgravity Experiment. Metall. Trans. A, vol. 19, no. 8, Aug. 1988, pp. 1945–1953.

Winsa, E.A.; et al.: Flight Hardware and Tele-Operations Supporting the Isothermal Dendritic Growth Experiment Aboard the Space Shuttle. AIAA Paper 89–0863, Jan. 1989.

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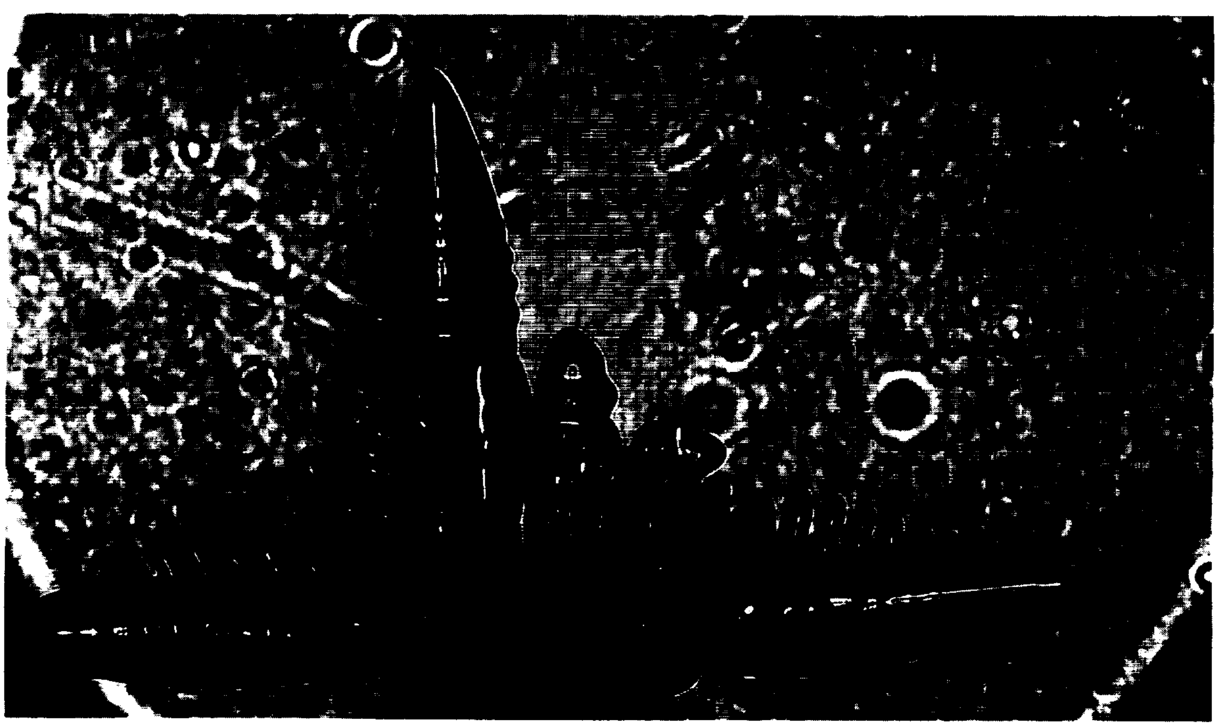

Dendrite growing in the IDGE apparatus.

Space Station *Freedom*

Systems Engineering and Integration

Panel Assembly Tested for Solar Dynamic Concentrator

NASA Lewis successfully tested a solar dynamic concentrator panel assembly at the Marshall Space Flight Center's (MSFC) Neutral Buoyancy Simulator (NBS) Facility during the period July 11 to September 18, 1990. This underwater test series focused on the concentrator for the Space Station *Freedom* solar dynamic power module by evaluating on-orbit assembly procedures and latch mech-anisms of a large erectable structure. This test was the first underwater assembly testing of *Freedom's* solar dynamic hardware.

A neutral buoyancy simulator is a deep-water tank that simulates the weightlessness experienced in space by making the test subjects and the test articles neutrally buoyant in the water so that they neither sink nor float. Flight experience indicates excellent correlation between the effects of neutral buoyancy simulations and the effects of actual weightlessness.

The solar dynamic concentrator is a large erectable structure designed to be assembled by astronauts on orbit. It consists of 19 hexagonal panels with self-locking ball-and-socket latches located at the panel corners. These latches connect the panels to form the complete reflector. The underwater mockup's concentrator panels were designed to simulate the baseline concentrator panels. Latch guides to aid in alignment were fabricated and installed on the panels.

The latches functioned flawlessly throughout the testing. They were engaged and disengaged approximately 50 times during

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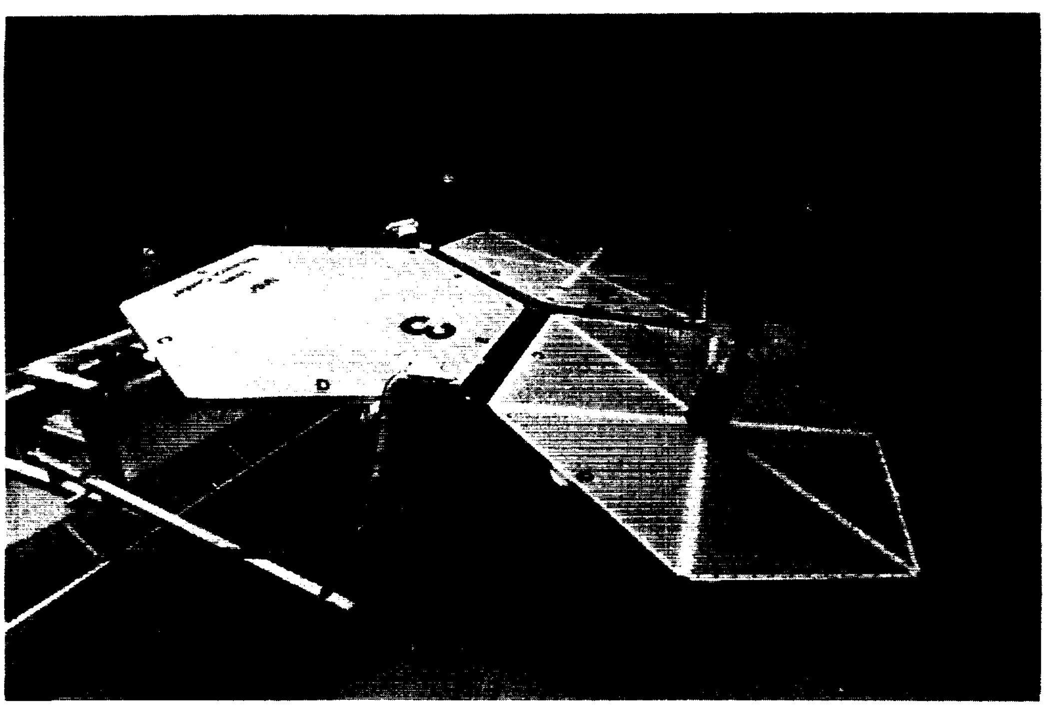

Three-segment solar dynamic concentrator in Neutral Buoyancy Simulator.

testing and no significant problems occurred. Ten different orientations were evaluated by two suited "astronauts." An orientation where the panels were horizontal and perpendicular to the astronauts was selected as the best assembly orientation. It offered good handling control of the panels and a good view of the latches. The latch guide system, which consisted of panel-to-panel gross guides, worked very well. Alignment during some of the test orientations would have been extremely difficult without them. This precision latch and guide concept and the assembly orientations and procedures worked out during this test will enable successful on-orbit assembly of large space structures.

The tests also helped to identify extravehicular activity (EVA) tools, restraints, and handholds and hardware design changes to ensure that evolving designs are EVA compatible. These tests were a critical part of the early design evaluation process that will reduce technical risks in the development of the baseline solar dynamic concentrator.

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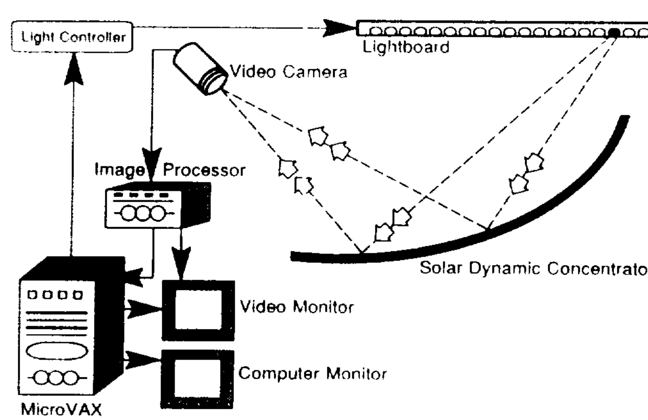
Solar Dynamic Concentrator Is Optically Evaluated

NASA Lewis has successfully demonstrated a computerized optical evaluation system for use on solar concentrators. The system, called a digital image radiometer (DIR), was procured from the McDonnell Douglas Astronautics Company. Its purpose is to aid in evaluating the optical properties of the solar concentrator and its reflective surface, which is composed of contoured, mirror-like facets. The DIR system provides alignment information as well as slope error and radius of curvature measurements of the concentrator surface.

The DIR system has the following components: a video camera, a ceiling-mounted lightboard with 1127 lights, a Digital Equipment Corporation microVAX computer, and a dedicated image processor. The ceiling lights sequentially illuminate the concentrator, and light is reflected to the camera from portions of the concentrator. The image detailing the size, orientation, and location of the reflected regions is captured by the video camera and processed before the next light is turned on. The information from all the lights is then combined to yield optical property measurements and a determination of the concentrator's contour. The contour data are then compared with a theoretical data base to determine any necessary alignment corrections. The value of this system lies in the power to obtain large quantities of data in a short period of time because of the system's automation and high resolution.

NASA Lewis personnel performed the acceptance testing on a prototype solar concentrator that had been previously characterized with a laser scanning system. Comparing the alignment of the reflective surface as characterized by the two systems showed close agreement.

The DIR system has been used as a evaluation tool in concentrator tests. Structural repeatability tests demonstrated that the 19-panel concentrator could be disassembled and then reassembled and still maintain optical alignment. Another series of tests offered insight into the sensitivity of facet tilt error under varied concentrator structural loading conditions. Other studies have investigated DIR measurement repeatability and facet radius-of-curvature variations and have compared optical properties from facets produced with several different materials and processes.



DIR system components.

The DIR system has given NASA Lewis experience with solar concentrator optical evaluation systems and has demonstrated its capability to characterize and align the reflective facets of solar dynamic concentrators.

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Projected-Image System Developed for Optical Checkout of Solar Dynamic Concentrator

An optical system for evaluating parabolic reflective structures was developed and tested at NASA Lewis. This projected-image system was installed to verify proper operation of an existing more complex optical measuring system. Using the projected-image system showed that it can readily measure concentrator alignment and reflective facet characteristics. Thus, it augments the capabilities of the more complex system.

The system operates as follows: A high-intensity light source at the focal point of the solar concentrator under test is reflected by the concentrator facets and linearly projected onto the ceiling of the test facility. The light source illuminates the entire concentrator. Light paths start at the parabolic focal point and go to each of the facets. They are then projected onto the ceiling. If the facet contours exactly matched the ideal parabolic contours, the reflected rays would all be parallel and the projections would be exactly linear. Analysis of these projected images shows whether the facet alignment and the facet contour deviate from the ideal parabola.

The projected images were in good agreement with images predicted by the complex optical measuring system, verifying proper operation of both systems. The projected-image system has also been used to provide a quick visual check of facet contour, alignment, specularity, and symmetry. This system is a very simple, yet effective, means of obtaining qualitative as well as quantitive concentrator optical characteristics.

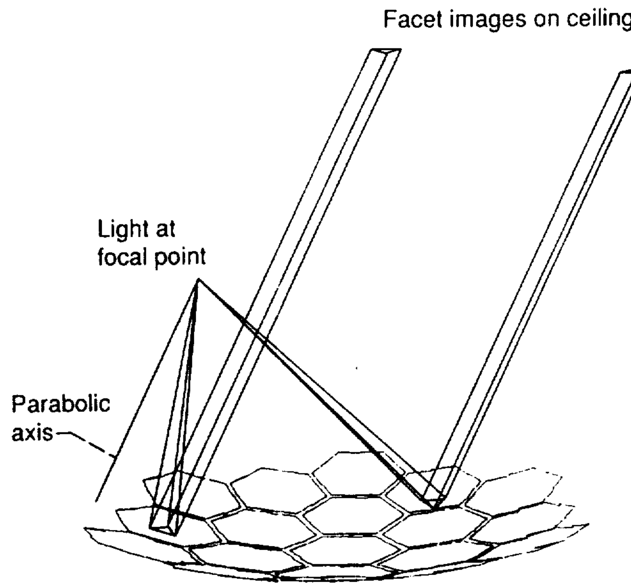

Diagram of projected-image optical system.

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Computer Code Used to Study Solar Dynamic Engine System

A comprehensive in-house computer code called CCEP, or Closed Cycle Engine Program, has been evolving within the Space Station *Freedom* Directorate at NASA Lewis. This computer code can design and analyze the performance of dynamic space electric power systems that are based on the Brayton thermodynamic cycle. This Brayton cycle is a closed-cycle version of an aircraft gas-turbine engine that can use an inert gas mixture rather than air and produces electricity rather than thrust. The CCEP code has been used to support the development of solar dynamic power modules for Space Station *Freedom*.

Over the past year CCEP has been used to make independent assessments of the solar dynamic power module design and performance. Twelve internal reports and four presentations have documented these system and component studies. In general, orbital performance estimates by the contractor team correlated with the in-house results. However, differences were found between the analyses for least power system mass. Although the differences only represent a 4-percent change in total mass, attempts are being made to resolve them.

Beyond normal assessments of contractor results, other complementary studies were made with CCEP. One particular study examined surface temperature distributions within the solar heat receiver of the solar dynamic module. The object of the study was to aid in evaluating cyclic stresses and estimating the heat receiver's useful life. Two large matrices are needed for radiosity calculations within the receiver cavity to properly evaluate its transient operating temperatures. Most of the incident solar flux within the cavity is absorbed by salt canisters that surround 82 equally spaced gas heat transfer tubes around the cylindrical inner wall. Active gas flow length is 8 ft and there are 96 canisters per tube. By melting the salt during the sunlit portion of an Earth orbit, part of this heat is stored for later use during passage through the Earth's shadow. Thus, heat is continuously provided to the working gas. Because of the large memory requirements and complexity of transient calculations the Cray-2 computer at Ames Research Center's Numerical Aerodynamic Simulation Facility was used. The highest surface temperature distribution predicted for the best flux-tailored mirror/receiver arrangement was 1546 °F. This localized peak wall temperature occurred at sunset under minimum-insolation and orbital energy-equilibrium conditions (third orbit). Each orbital calculation required an hour of Cray-2 processing time.

Two other complementary studies were made with CCEP during 1990. One estimated the turbomachinery runaway speed in case of a total loss of system controls. Analytically generated turbine and compressor maps that emphasized overspeed performance projections were supplied by, respectively, the Army's Propulsion Directorate at Lewis (AVSCOM) and the Lewis Internal Fluid Mechanics Division. Runaway speeds were found to be well above the third critical speed, or shaft bending mode, and therefore may not result in catastrophic loss of the turbomachinery. The other complementary study, begun later in the year, evaluated further design alternatives for the solar heat receiver. Effects of nonuniform axial distributions of the heat storage salt within the receiver were included to limit the amount of salt superheating and thereby reduce the peak salt canister temperature. Preliminary results indicate that a substantial peak temperature reduction (about 80 deg F) may be achievable along with a mass reduction. Strength properties for the Haynes containment material are such that receiver life expectancy should no longer be an issue with such a reduction in peak temperature in spite of the cyclic temperature environment.

Major CCEP additions this year included steady-state design and performance subroutines for gas-to-liquid heat exchangers and subroutines for transient recuperator performance. Development has been nearly completed on transient capabilities for the gas-to-liquid heat exchanger. Such capabilities represent the remaining missing piece needed for a thorough analysis of transient thermal performance of solar dynamic power modules.

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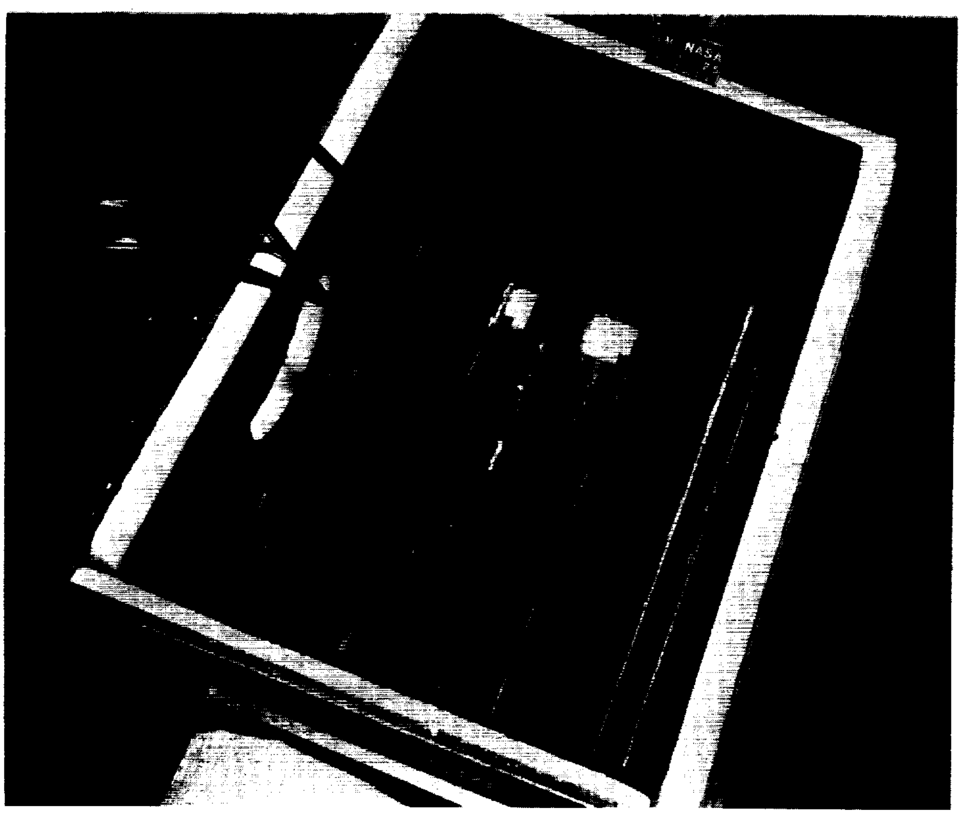
Receiver Thermal Energy Storage Canisters Tested and Analyzed

The solar dynamic power module (SDPM) being developed for Space Station *Freedom* uses a phase-change salt contained in many small annular metal canisters to store thermal energy. In *Freedom*' 91-min orbit, about one-third of the time is spent in the Earth's shadow, where sunlight is not available. Thus, energy must be stored by the SDPM for use during these extended periods of darkness to enable continuous electric power production for *Freedom*. The phase-change salt stores thermal energy as it melts near 1400 °F during the sunlight portion of *Freedom's* orbit. This stored energy is then given up as the salt slowly freezes while *Freedom* is in the Earth's shadow. Analyses and ground testing of these thermal energy storage (TES) canisters have been performed at NASA Lewis. The goal of this work is to better understand the melting and freezing behavior of the phase-change salt in order to guide the design of future TES canisters for use in the SDPM. One way in which understanding has been enhanced is through the use of computer-generated, video tape animations prepared to illustrate the salt melting and freezing processes.

During 1990, computer programs were developed to analyze one- and two-dimensional TES canister phase-change heat transfer. The governing equations were solved by using an explicit, finite-difference numerical technique. Models of liquid-salt free convection and void heat transfer (i.e., heat transfer across canister regions not containing salt) were included. Canister temperatures and the distributions of solid and liquid salt were predicted for simulated Space Station *Freedom* orbits and for ground test cycles.

Results of these analyses indicate that canister heat transfer is dominated by heat conduction within the canister walls. Approximately 70 percent of the heat transfer in the radial direction occurs by conduction within the canister sidewalls. This canister design attribute helps to maintain wall temperatures at or near the salt melting point throughout the melting/freezing cycle. In addition, heat transfer effects due to various void distributions and liquid-salt free convection are minimized. Therefore, differences in canister temperatures predicted for operation on *Freedom* (in near zero gravity) and those measured during ground tests (in normal gravity) were surprisingly small (i.e., less than 25 deg F).

A video tape animation of the numerical results for several cases analyzed was prepared by the Lewis Advanced Graphics and Visualization Laboratory. The animation visually depicts canister temperatures and



TES canisters in test chamber.

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salt phase distributions through the combined use of color fringe and isotherm contour-plotting techniques. Results are displayed in real time at 100:1 or 300:1 time compression ratios, which allow viewing of a 91-min orbital cycle in as little as 18 sec.

Experiments were also performed with three TES canisters. The experimental apparatus was set up to simulate the orbital heating and cooling conditions that canisters will experience while operating on *Freedom*. The canisters were tested in three different orientations with respect to gravity and the direction of external heating. Temperature data collected indicated that canister thermal performance was within pretest expectations and not greatly affected by test orientation. Canister temperature data were in excellent agreement with analytical prediction. Thus, canister phase-change heat transfer is fairly predictable and amenable to engineering analysis.

Using the analytical computer programs, validated with ground test data, and the visual animation techniques, Lewis engineers will be able to guide the design of a lower weight, more reliable canister for the solar dynamic power modules on Space Station *Freedom*.

Bibliography

Kerslake, T.W.; and Ibrahim, M.B.: Analysis of Thermal Energy Storage Material With Change-of-Phase Volumetric Effects. Proceedings of the 12th Annual ASME International Solar Energy Conference, ASME, New York, April 1990, pp. 315–325. (Also NASA TM-102457.)

Kerslake, T.W.; and Ibrahim, M.B.: Two-Dimensional Model of a Space Station *Freedom* Thermal Energy Storage Canister. 25th Intersociety Energy Conversion Engineering Conference, Vol. 2, AIChE, 1990, pp. 151–159. (Also NASA TM-103124.)

Kerslake, T.W.: Multi-Dimensional Modeling of a Thermal Energy Storage Canister. NASA TM-103731, 1991.

Kerslake, T.W.: Experiments With Phase Change Thermal Energy Storage Canisters For Space Station *Freedom*. Submitted for publication to the 26th Intersociety Energy Conversion Engineering Conference, Aug. 1991.

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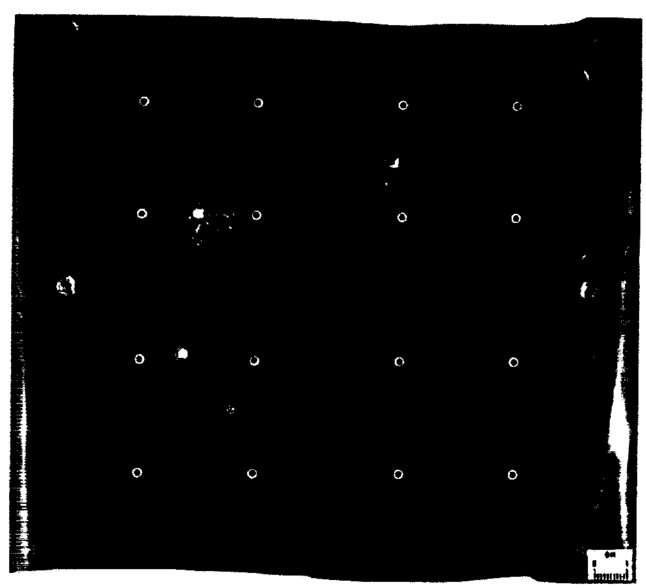
Photovoltaic Power Module

Hypervelocity Particle Impact Testing Performed on Solar Cells

Space Station *Freedom* must withstand micrometeoroids and man-made orbital space debris traveling at hypervelocity speeds. Impacts by these particles have the potential to damage the solar arrays and degrade their performance. Such damage could limit the ability of the arrays to provide the minimum peak power required for safe operation.

NASA Lewis has conducted a test program to investigate the vulnerability of Space Station *Freedom* photovoltaic arrays to hypervelocity particle impact damage. A series of tests were developed that used a four-cell solar array coupon manufactured by the Lockheed Missiles and Space Company. Each cell was subjected to impact by a 1/64-in. (0.4-mm) diameter spherical aluminum projectile launched from a two-stage light gas gun at a velocity of 7 to 8 km/sec. The projectile firings were conducted at the NASA Johnson Space Center's Hypervelocity Impact Research Facility. Peak power profile measurements were recorded to assess the percentage of performance degradation.



Solar array cells after particle impact testing.

Projectiles fired in the first series of tests impacted the front (or glass) side of the array. All impacts occurred normal (0°) to the array surface. The second series of projectile firings comprised a matrix of impacts on the front and back sides and at angles normal and oblique (45°) to the array surface. The peak power efficiency dropped by 0.7 to 3.5 percent per impact, but the solar cells remained intact.

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Nickel/Hydrogen Cells Tested

NASA Lewis and its contractors are responsible for designing and fabricating the electric power system for Space Station *Freedom*. *Freedom* will circle the Earth every 90 min in a low Earth orbit (LEO). Approximately 55 min of this orbit will be in sunlight and 35 min will be in the shadow of the Earth (eclipse). In order to supply continuous power over the orbit, the electric power system must not only provide power during the sunlight portion by means of solar arrays, but must also supply energy for use during eclipse. Nickel/hydrogen (Ni/H_2) cells were chosen as the energy storage system for *Freedom*. Because of the limited Ni/H_2 data base on life and performance characteristics in a LEO regime, NASA Lewis began two test programs: one in house and one at the Naval Weapons Support Center (NWSC) in Crane, Indiana.

For the in-house test program, Lewis has built a computer-controlled Ni/H_2 cell laboratory with a data acquisition system to screen a large number of cell designs. Cells were purchased from three vendors through existing Lewis contracts with Yardney Technical Products, Eagle-Picher Industries, and Hughes Aircraft Company. The resulting 39-cell test matrix consists of 13 different cell designs including both 50- and 65-Ahr capacity cells. All cells have successfully completed acceptance, vibration, and characterization testing and are currently undergoing LEO life testing at a 35-percent

Ni/H_2 cell test chamber at Lewis.

depth of discharge (DOD) and at either -5 or 10 °C. As of January 1991, all cells have successfully completed over 1 year of life testing (5840 cycles), reaching 6400 to 10,800 cycles.

The Naval Weapons Support Center was contracted by Lewis through an interagency order to characterize and life test a statistically significant number of Ni/H_2 cells for the purpose of verifying the Space Station *Freedom* requirement of 5-year life at 35 percent DOD. The test matrix consists of 130 Ni/H_2 cells from each of three vendors: Yardney Technical Products, Eagle-Picher Industries, and Gates Aerospace Batteries. Each vendor will supply 50 "standard" 65-Ahr cells that represent a low-risk, state-of-the-art LEO design. They will also supply 20 "advanced" 65-Ahr cells and 60 "advanced" 81-Ahr cells. For the "advanced" design the vendors were directed to include at least two recent technology developments that improve cycle life and electrical performance. All cells were procured through separate Lewis contracts. As of January 1991, all Eagle-Picher and all Yardney cells have been delivered to NWSC. All 70 Yardney 65-Ahr cells have successfully completed acceptance, vibration and characterization testing. Sixty of these cells, (40 "standard" and 20 "advanced") are currently on life test in series-connected 10-cell and 5-cell packs. These cells have accumulated between 200 and 3000 cycles. Life testing is at both -5 and 10 °C and 35- and 60-percent DOD. Other delivered cells from both vendors are in acceptance testing. Thirty additional 65-Ahr standard cells have been ordered from Gates for charge control testing. These and the other 130 cells from Gates are scheduled for delivery by August 1991. NWSC will also perform storage tests on cells from each vendor.

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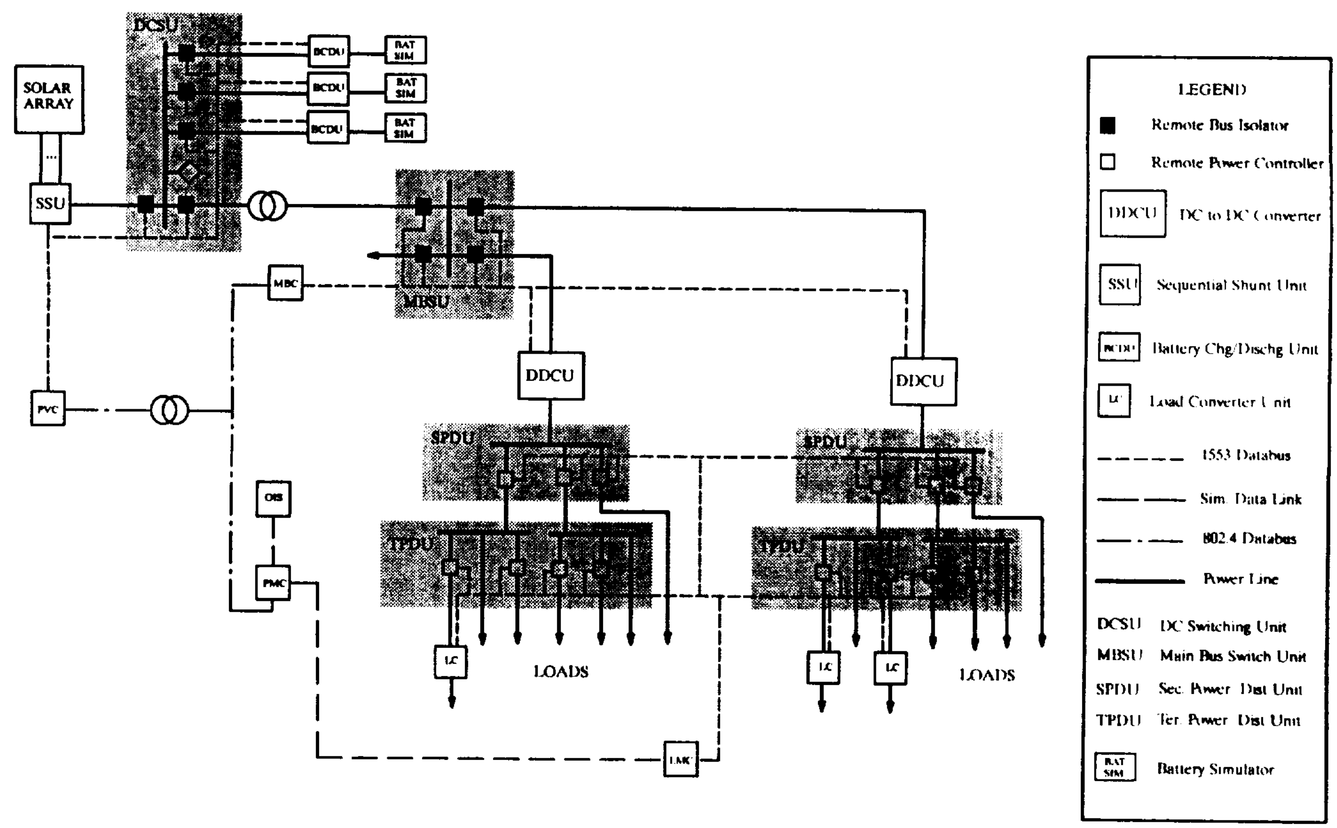
Electrical Systems

Power Management and Distribution DC Test Bed Assembled

The Space Station *Freedom* Program is now pursuing the development of a direct-current power generation and distribution system that functions like a terrestrial utility power system. Although *Freedom's* power system uses dc for distribution, converters are needed to control the power and convert it to a different type for user applications. The large number of converters used in such a small system presents problems never before encountered in aerospace or terrestrial power systems. To solve these problems, NASA Lewis developed and assembled a test bed that could address the system design issues associated with this type of power, such as power generation control, protection system coordination, and power quality.

The power management and distribution dc test bed is located in the Power Systems Facility (PSF). It incorporates all the necessary component and assembly units



Space station power management and distribution dc test bed.

needed to functionally represent the space station power system. The accompanying single-line schematic diagram shows the architecture of the test-bed system. Source power for the test bed is obtained from the solar array field located next to PSF and is regulated through the sequential shunt unit (SSU). The battery charge/discharge unit (BCDU) allows control of the battery storage unit and is connected to the source and primary distribution system though the dc switching unit (DCSU). In the primary distribution system the main bus switching unit (MBSU) interconnects the power sources to the dc-to-dc converter units (DDCU). The DDCU's lower and regulate the system voltage for distribution to the secondary system, which is interconnected to user loads and load converter units (LCU's) through secondary and tertiary distribution units (SPDU/TPDU). This test-bed system and its supporting facility are unique. It is the largest spacecraft type of test bed that has been built to support dc power system technology work.

Lewis engineers developed the test-bed architecture and performed system engineering and integration. The following contractors were involved in developing the test-bed system, the software, and the components and assembly units:

(1) Rockwell International, Rocketdyne Division: system engineering and software.
(2) TRW, Space System Division: SSU, BCDU, DDCU.
(3) Westinghouse, Electrical Systems Division: remote bus isolator, remote power controller, and LCU

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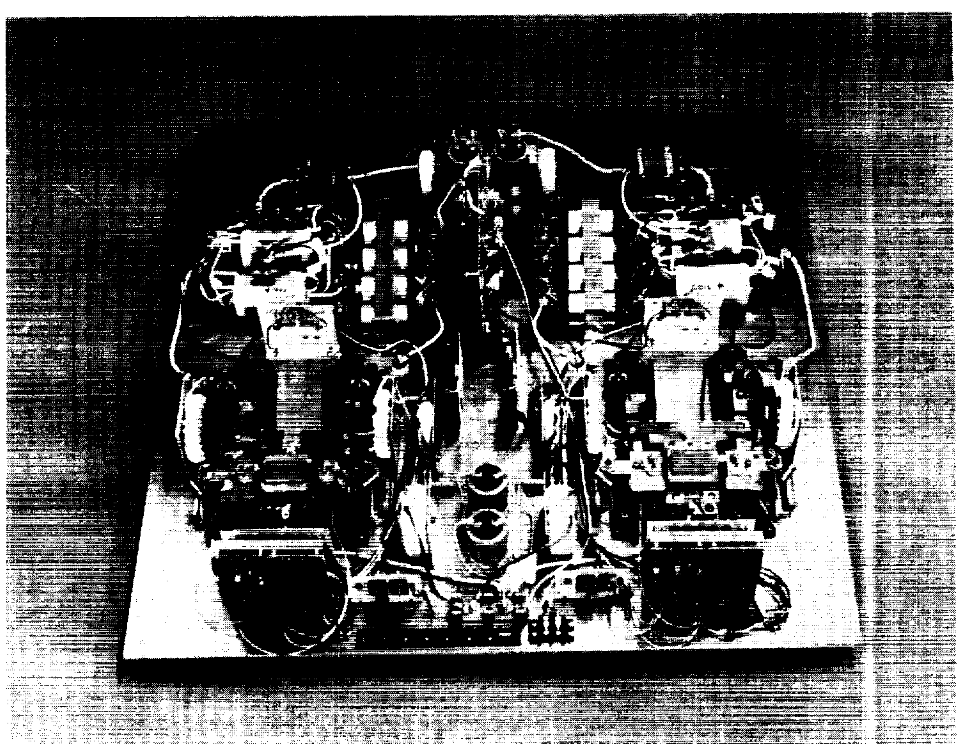
Headquarters program office: OSS

DC-to-DC Converter Unit Being Tested

The Space Station *Freedom* electric power system uses direct-current power for distribution and incorporates several regulating elements to convert and condition the electric power prior to delivery to the power user. The secondary distribution system is regulated by a dc-to-dc converter



dc-to-dc converter unit.

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unit (DDCU) that converts the primary system voltage from 160 V dc to 120 V dc for distribution to user loads. This regulating element is a critical unit because it is the interface to all user loads and must be capable of providing conditioned power regardless of the load types powered by the unit. The power management and distri-bution dc test bed located in the Power Systems Facility (PSF) at NASA Lewis incorporates several DDCU's.

The DDCU currently under test in PSF was developed by TRW's Space Systems Division and incorporates many features expected in the flight unit that will be launched for the space station. It is capable of providing up to 12.5 kW of power from two parallel 6.25-kW modules. The unit can be controlled and monitored from a computer through a MIL-1553 data-bus interface. The DDCU includes a common input filter element that feeds two phase-displaced, 20-kHz, series-resonant dc-to-ac inverters having rectifier elements and first-stage output filters followed by a common second-stage output filter. The DDCU has been designed to allow parallel operation of two units and can adjust the power sharing between the units to maximize power transfer to the loads. The same power-sharing circuit also prevents unscheduled load changes from overloading the power sources and causing brownout of the system. Telemetry data from the DDCU consist of input voltage and current and output voltage, current, power, and power sharing.

Integration tests performed on the unit have demonstrated its control loop response, output power quality, and interface command and control. Further tests of the units will be performed in the test-bed power system in support of the Space Station *Freedom* Program.

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High-Current DC Remote Bus Isolator Delivered

The Space Station *Freedom* electric power system will be expected to provide optimal power availability, even under outage conditions. One possible way of achieving this aim is to permit cross-tying of primary power channels. While offering operational flexibility, tying power channels places greater demands on the switchgear by increasing the current available at any point in the tied system.

NASA Lewis has conducted a program to assess the requirements for a high-current switch, to evaluate technology for meeting the requirements, and to build and demonstrate a breadboard that meets the requirements. The result is the high-current remote bus isolator (HRBI). The HRBI is rated at 160 V dc and carries 335 A continuously while interrupting 1900 A. It also incorporates remote-control and protective features called for by the Space Station *Freedom* design.

The requirements study was performed jointly by Lewis and Rockwell International's Rocketdyne Division and was based on a four-channel station with solar dynamic growth options. Results of this study indicated that the isolator must operate fully bidirectionally, carry 50 kW continuously, interrupt 1900 A, withstand fault transients, sustain a 150-W power loss, survive many switching operations, utilize existing technology, and incorporate remote-control and protective features consistent with the Space Station *Freedom* design concept.

Westinghouse Electrical Systems Division of Lima, Ohio, was subcontracted by Rocketdyne for the design and fabrication phases of the project, with technical management by Rocketdyne and Lewis.

The design concept study evaluated electromechanical relays and various semiconductor switches. The selected concept uses unidirectional field-effect transistor modules with integral shunt and drive circuits to limit current at about 250 A. These modules are connected to provide the desired rating and bidirectionality. A contactor may

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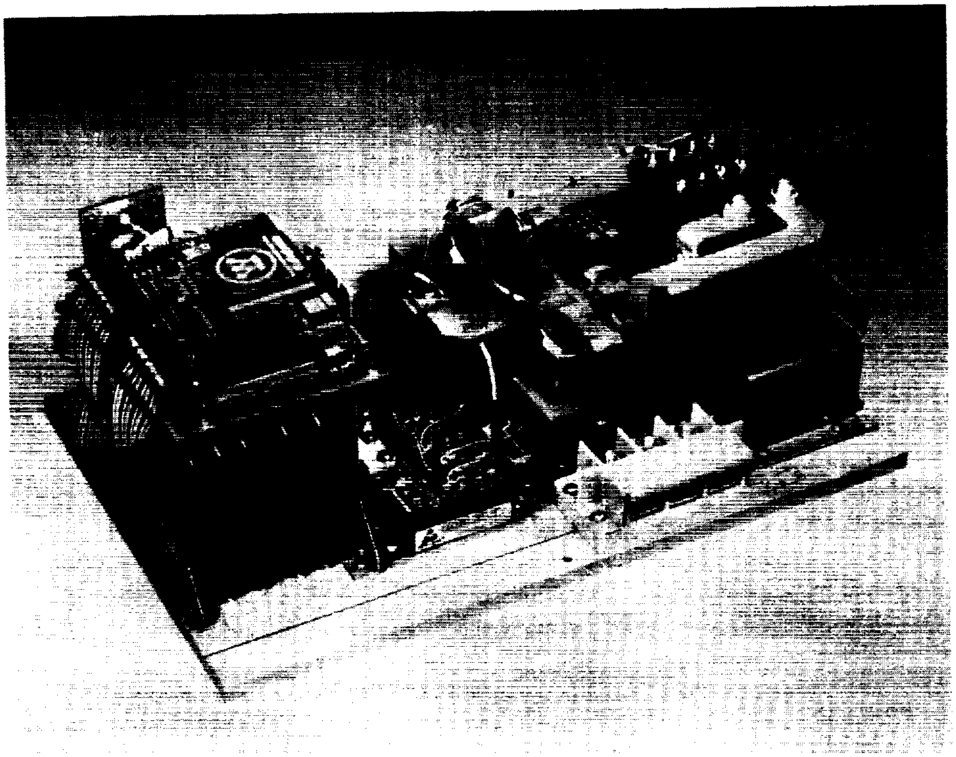

High-current dc remote bus isolator.

short circuit the semiconductor switch during "carry" operation to reduce losses.

Two breadboard HRBI's were tested at Westinghouse and delivered to Lewis for further testing. One contains a carry relay for low losses; the other is packaged to limit transient currents to below 2000 A.

The units will complete testing in the power management and distribution (PMAD) dc test bed in the Power Systems Facility.

Each unit contains a dual MIL-1553 communications bus interface for full remote control and programming. Additionally, the HRBI is equipped for use with the differential protection system designed for the PMAD dc test bed.

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DC Remote Bus Isolator and Remote Power Controller Being Tested

The Space Station *Freedom* electric power system uses solar arrays and batteries with peak generation and storage capacity up to 480 kW. The system is operated at a much smaller power level by managing the loads applied to the system and channeling the system into isolated power islands. This also reduces the total fault current that must be interrupted in order to protect the power channel from a blackout. A blackout would occur if the electrical fault was not removed by the distribution switchgear. The current size of a power channel on the space station is 60 kW, resulting in a fault current of 380 A. Two types of switchgear unit have been developed for use in the primary and secondary distribution systems of the power management and distribution dc test bed located in the Power Systems Facility.

The remote bus isolator (RBI) is used within the primary network and is a hybrid switch consisting of a relay in parallel with a power transistor. This type of switch enables low-loss operation and reduces stress on the unit by utilizing the best operating characteristics of the relay and solid-state devices. The switch is rated at 25 kW and 160 V dc but can interrupt a fault current of 400 A. Two types of RBI were developed for the test bed by the Electrical Systems Division of Westinghouse. The first unit developed was a unidirectional device and is used wherever the current flows in a single direction. The second unit is bidirectional and can be used to interrupt currents in both directions.

The remote power controller (RPC) is used within the secondary distribution network and is an all-solid-state switch with a power transistor. This type of switch enables current-limiting operation for turnon and turnoff of the device under overload and fault conditions. Current limiting reduces the voltage and current transients that would occur in the system if no current limiting were done. A family of RPC's with different power ratings was developed for the test bed by the Electrical Systems Division of Westinghouse. Both the RBI's and RPC's incorporate a MIL-1553 data-bus interface that allows monitoring of voltage, current, and power and system protection features that allow for setable overcurrent thresholds, undervoltage, and differential current tripping.

Integration tests performed on the RBI's and RPC's have demonstrated control loop response, protective features, and interface command and control. These units will be tested further in the test-bed power system in support of the Space Station *Freedom* Program.

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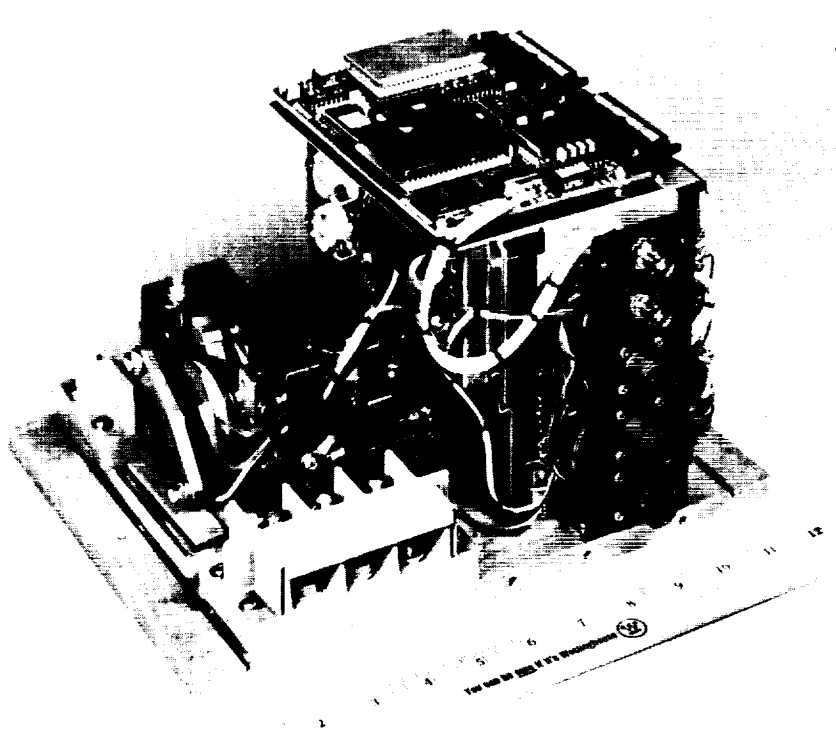
Sequential Shunt Unit Breadboard Completes Tests

The Space Station *Freedom* electric power system (EPS) derives its power from several solar array blankets. During the 55-min sunlight portion of *Freedom's* orbit the solar arrays are used to power scientific experiments, to run vital life-support systems, and to charge



dc remote bus isolator and remote power control unit.

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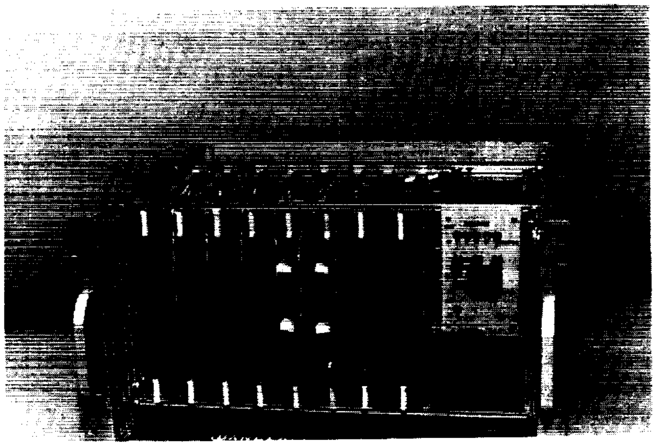

Sequential shunt unit.

batteries. However, since the arrays are unregulated power sources, a sequential shunt unit (SSU) is needed to provide regulated power to the EPS primary bus.

TRW Space Systems of Redondo Beach, California, was contracted to design and build two SSU's to undergo testing here at NASA Lewis. The TRW SSU is capable of regulating an 82-string solar array and can supply up to 35 kW of regulated 160 V dc to the primary power bus. The TRW SSU regulates by applying the correct number of strings to the bus and "shunting" the remaining strings' power back to the array. It has programmable output voltage and telemetry through its MIL-1553B data-bus interface and has built-in and external fault protection circuits. It uses active regulation and can respond to both line and load changes in the system.

One SSU has been integrated with the 80-string solar array field adjacent to the Power Systems Facility and has completed component-level tests. The SSU has displayed good voltage regulation and good response to short circuits. The SSU will eventually be integrated into the power management and distribution dc test bed for complete EPS stability and power quality tests.

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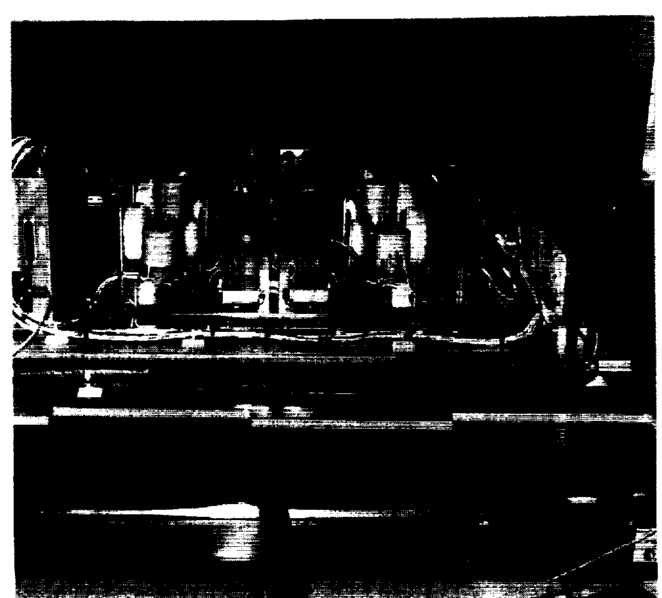
Battery Charge/Discharge Unit Breadboard Is Integrated and Tested

Space Station *Freedom* is currently designed to operate in low Earth orbit. Its proximity to the Earth causes frequent cycles from sunlight to eclipse. During eclipse the space station will derive its power from several banks of nickel/hydrogen batteries. However, since the battery voltage is lower than the primary bus voltage, a battery charge/discharge unit (BCDU) is needed to interface the batteries to the bus.

TRW Space Systems of Redondo Beach, California, was contracted to design and build three BCDU's to undergo testing at NASA Lewis. The TRW BCDU is a 6-kW unit utilizing a bidirectional "buck-boost" power stage to charge and discharge batteries. The BCDU controls the charge rate or current into the battery during charging and regulates the output or bus voltage during discharge. The BCDU has a maximum charge rate of 55 A and an output voltage range of 140 to 160 V dc. The BCDU has five programmable setpoints that allow the user to tailor the BCDU controls and vary BCDU power sharing and transitions.

Currently, one BCDU has been integrated with a battery simulator and has completed component-level tests. The BCDU displayed good current regulation during charge and



Battery charge/discharge unit breadboard.

excellent voltage regulation during discharge. The BCDU will eventually be integrated into the power management and distribution dc test bed for complete system tests.

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Operations

Power System Assembly and Maintenance Testing Performed

Space Station *Freedom's* electric power system consists of photovoltaic power modules that track, capture, and store the Sun's energy. These photovoltaic power modules must be assembled and maintained in space's zero-gravity environment by astronauts and robots. In order to reduce the intuition involved in the design process and to provide sound practical assembly and maintenance concepts, a series of neutral buoyancy extravehicular activity (EVA) simulations are being conducted during the development phase of the program.

Focusing on one of the crucial elements of the space station—the solar array assembly—NASA's Lewis Research Center and Johnson Space Center conducted the first Weightless Environment Training Facility (WETF) test at Johnson. This facility closely simulates the environmental conditions in space by using the neutral buoyancy effects of water.

The hardware, designed and fabricated at Lewis, concentrated on the solar array containment boxes that extend from both sides of a mast canister. These components fit inside a beta gimbal, which is built around the truss structure supporting the space station. In space, these boxes unfurl the 112-ft solar arrays. Fourteen space-suited astronauts performed the assembly and maintenance as it would be done on orbit. The tests eliminated the deployment motors, reduced and reevaluated the transition structures, reevaluated the attachment mechanisms, and provided an understanding of EVA anthropometrics—all of which are invaluable to the design engineer.

This series of tests is being coordinated through the EVA Systems Working Group. Future tests will address installation and maintenance of the integrated equipment assembly as well as the building of the entire electric power system.

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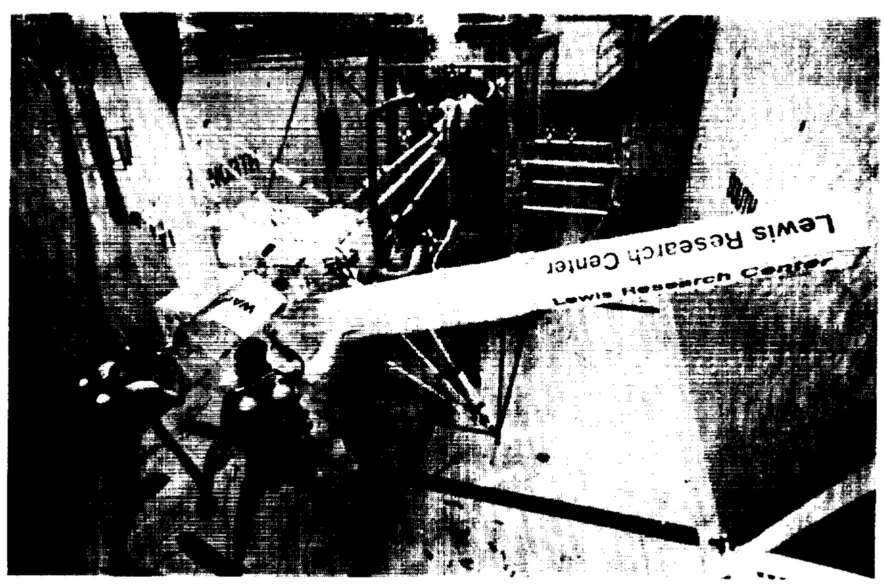

Neutral buoyancy test of solar array beta gimbal.

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Engineering and Computational Support

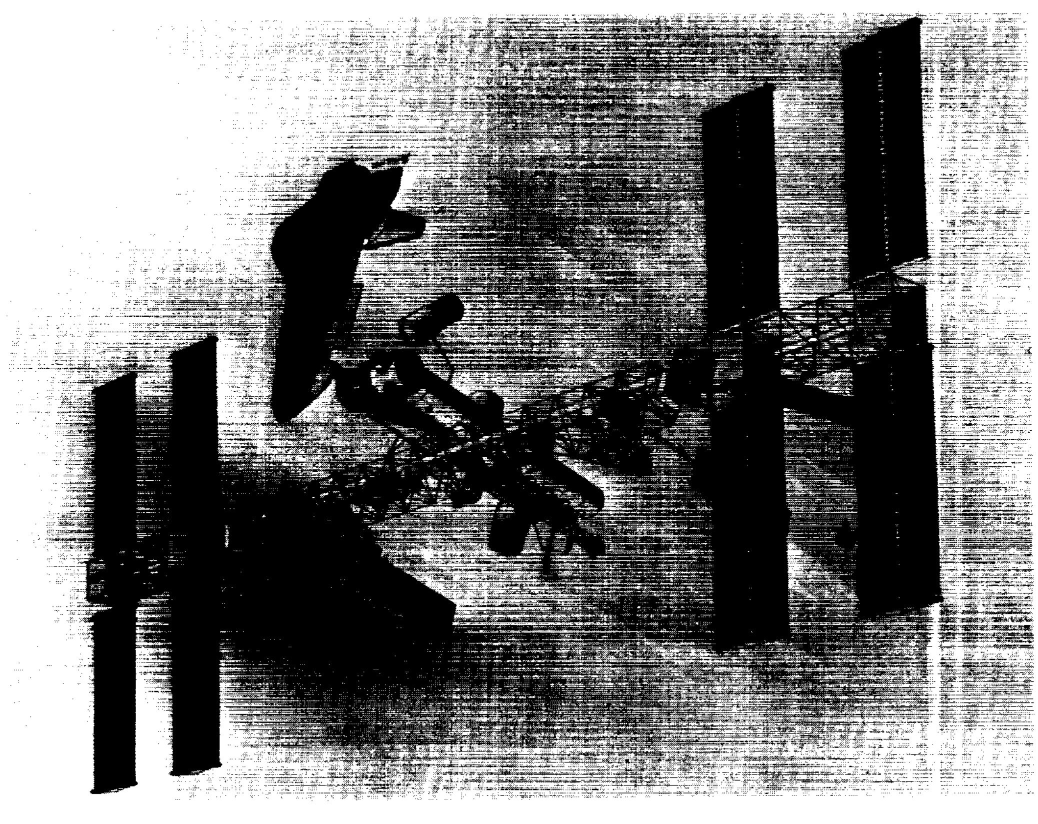
Structural Systems

Program Analyzes Spacecraft Control-Structure Interaction

CO–ST–IN, short for COntrol-STructure-INteraction, is a computer program written by the Structural Dynamics Research Corporation (SDRC) under the direction of NASA Lewis. Originally envisioned as a tool for transferring data among various structural and control system analysis programs, it has developed into a fully integrated computational tool enabling NASA Lewis to effectively predict the very complex control-structure interactions occurring in modern spacecraft designs.

The current evolution in spacecraft design is toward larger, lighter, and more flexible structures. Space Station *Freedom* is an example of such a structure. A potential problem that arises in these designs is that the control systems used to position various components of the spacecraft can interact with the flexibility of the structure. These control-structure interactions can, in some cases, lead to unstable control behavior. Additionally, the forces generated by the control systems could significantly affect the loads generated within the spacecraft structure.

Analyses conducted at NASA Lewis using CO–ST–IN show that the control systems used to rotate the alpha joints of the space station can help reduce bending moments at the base of large photovoltaic arrays. Finite element models used in the analyses were very complex. Some models had over 1000 natural modes of vibration in the frequency range of interest even after CO–ST–IN's mode selection capability was applied extensively at the component level. Since simulations were



calculated in CO–ST–IN by using a very efficient simulation algorithm, modal selection was not necessary at the system level.

CO–ST–IN can transfer structural models from programs such as MSC/NASTRAN and I–DEAS to control system analysis programs such as EASY5, MATLAB, and MATRIXx. It can also transfer forces and moments generated by control systems back to the structural model for evaluation of internal loads. As an alternative, the coupled system, in the case of relatively simple control systems, can be simulated directly in CO–ST–IN. The option to calculate closed-loop frequencies in order to evaluate stability is also included.

The results of the CO–ST–IN simulations done at NASA Lewis will be used to help design components of the Space Station *Freedom* electrical power system.

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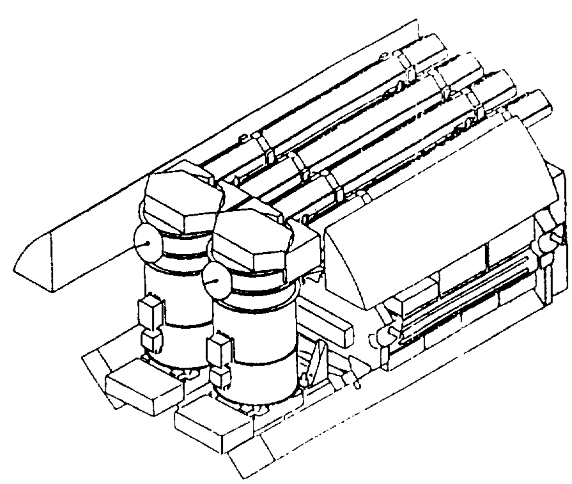
Advanced Dynamic Coupled Loads Analysis Developed

NASA Lewis has developed a new set of capabilities for more efficiently performing coupled loads analyses. These capabilities can now be used earlier and more often in designing spacecraft. They have been used to determine the design loads for a wide range of advanced systems including the Space Station *Freedom* power system, the Advanced Communications Technology Satellite (ACTS), and the Geostationary Orbit Environmental Satellite (GOES) and Solar and Heliocentric Observatory (SOHO) spacecraft, which are launched on Atlas-Centaur rockets.

The structural design loads on spacecraft systems are often caused by high-amplitude dynamic environments. For example, the maximum loads experienced by payloads launched on the space shuttle are generally produced during lift-off by solid rocket booster ignition vibration. The ability to analytically predict loads accurately and quickly is essential to the weight-efficient design of successful spacecraft. The process for calculating the structural response is a finite-element analysis called Coupled Loads. (Mathematical models of the individual components are "coupled" together for the analysis.) Because this has been a costly and time-consuming task relative to the spacecraft development schedule, less accurate methods of analysis have often been used.

There are four main phases in a coupled loads analysis. In the first phase, component models are developed for each major subsystem, such as the shuttle and the spacecraft. The component models are assembled in the second phase to form the coupled system model. Transient excitations for one or more dynamic loading events are applied in the third phase to determine transient responses. The final phase performs postprocessing to determine maximum responses. For advanced aerospace systems the models are usually very detailed and large. The number of load cases studied is also large in order to describe all major combinations of dynamic loads, such as solid rocket booster ignition and wind loads. Finally, an extensive number of physical responses may need to be recovered from the coupled loads analysis in order to thoroughly assess structural integrity. The specialized methodology



Space Station Freedom power system design for shuttle launch, recently analyzed for launch design environment by using advanced dynamic coupled loads methodology.

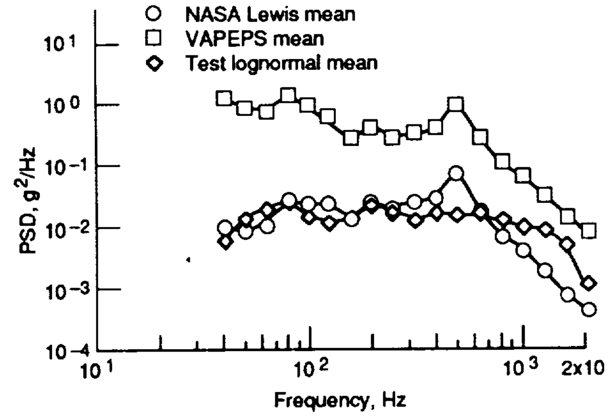
developed was created to minimize these effects in the analysis process.

A paper on this subject will be presented at the MSC/NASTRAN World Users Conference in March 1991.

Bibliography

Manella, R.T.; and Flanigan, C.C.: Advanced Coupled Loads Analysis. MSC/NASTRAN World Users' Conference, Mar. 11, 1991.

Lewis contact: Richard T. Manella, (216) 433-2596
Headquarters program office: OSS



Comparison of vibroacoustic prediction methods.

Using NASA Lewis Method in VAPEPS Improves Low-Frequency Vibroacoustic Predictions

VAPEPS (VibroAcoustic Payload Environment Prediction System) is a computer program that is based upon statistical energy analysis and is used to predict the vibroacoustic response of a structure. VAPEPS is managed by the Jet Propulsion Laboratory (JPL) and is currently sponsored by NASA Lewis. At NASA Lewis, VAPEPS is used to determine the component random vibration qualification levels for the Advanced Communications Technology Satellite (ACTS) and Space Station *Freedom*. VAPEPS is also used at NASA Lewis to predict the interior acoustic levels within Atlas-Centaur and commercial Titan expendable launch vehicle fairings.

It is well documented that VAPEPS overpredicts in the low-frequency range. To improve upon the low-frequency prediction, NASA Lewis developed an alternative modeling method for VAPEPS that is outlined in detail in reference 1. This alternative method is called the NASA Lewis Method. It should be used for vibroacoustic predictions of mass-loaded honeycomb panel structures, such as those typically found in modern spacecraft construction.

The NASA Lewis Method has been successfully benchmarked by comparing the VAPEPS predictions with the acoustic ground test data for three spacecraft panels. The NASA Lewis Method has been implemented into the latest version of VAPEPS by JPL.

The NASA Lewis Method is the recommended method for predicting the vibroacoustic response of unreinforced mass-loaded honeycomb panel structures.

Reference

1. McNelis, M.E.: A Modified VAPEPS Method for Predicting Vibroacoustic Response of Unreinforced Mass-Loaded Honeycomb Panels. NASA TM-101467, 1989.

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Headquarters program office: OSSA

Computational Support

Advances Made in Computation and Visualization

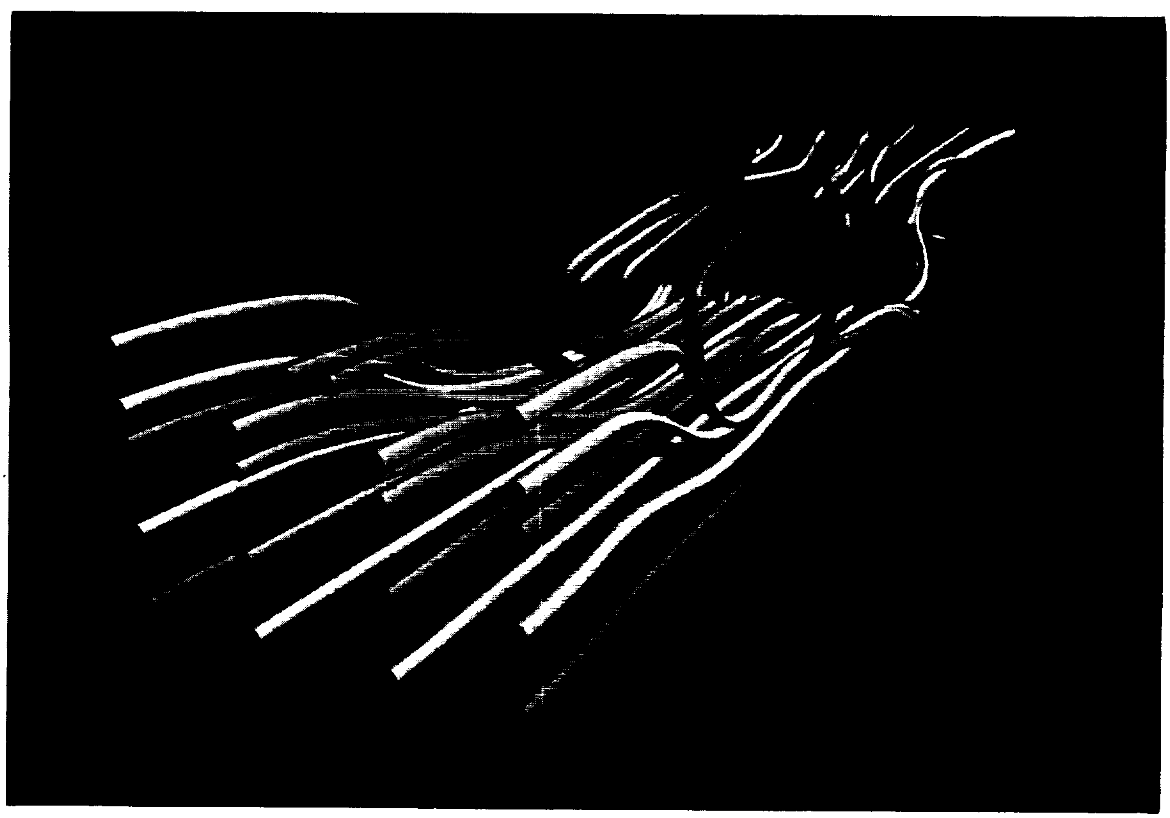
The Computer Services Division (CSD) is composed of system engineers, analysts, programmers, technicians, and operators who provide services beneficial to NASA Lewis. Such services include developing programs for both scientific and business applications; installing, operating, and maintaining computers; supporting microcomputers;

recording and processing data; training; assisting in data security; and integrating data, voice, telephone, and video.

In an effort to better serve the Lewis community, CSD has been heavily involved in researching users' needs in the area of computing. As a result, division personnel seek to purchase new equipment, to develop and redesign existing systems, and to develop a number of facilities.

System analysts in CSD maintain computers, such as Amdahl and Alliant mainframes and VAX minicomputers. In the past year the Convex C220 with two processors and the Cray Y/MP supercomputer were added. The Cray Y/MP is equipped with six central processing units, 128 million words of memory, 40 gigabytes of disk storage, and 128 million words of solid-state storage.

Also new to the division is the development of certain facilities that aid users to accomplish different tasks. One such facility is the Advanced Computational Concepts Laboratory (ACCL). At this facility Lewis researchers and computer scientists, as well as their counterparts in industry and academia, can combine their talents to explore newly emerging computing and communications technologies. Many researchers throughout Lewis use graphics for enhancement. CSD has developed powerful computer graphics software (Scientific Visualization Package) and combined it with a unique, state-of-the-art hardware facility. This facility is called the Advanced Graphics and Visualization Laboratory (G-VIS). The G-VIS houses specialized graphics devices like the Ultranet frame buffer, which uses the gigabit Ultranet network to display images from the Convex and Cray supercomputers at up to 20 images per second, and the Pixar volume imaging system, which displays volumetric data that arise in three-dimensional simulations or laser-scanned flow fields. The laboratory includes an extensive video animation facility created



Complex flow patterns visualized by the Scientific Visualization Package using smooth, shaded tube tracers.

to facilitate the use of video as a scientific research tool.

The Technology Demonstration Center (TDC) was created to serve the user community in two ways. The TDC is a place where computer vendors can display their products at Lewis and where users can test available products. With the ever-increasing interest in computing, the need for advancement in communications was not overlooked. A tiered network architecture has been implemented to support the broadbased computing and communications needs of the center. This type of network architecture offers efficient use of our networks by matching applications to bandwidth. Instead of lowering the percentage of effective bandwidth used by transmitting sparsely filled packets with significant protocol overhead, percentage utilization is increased by separating the applications into their respective places in the bandwidth spectrum.

Over the next year, data storage requirements at Lewis will reach 1000 gigabytes of data (one terabyte). Over the next 3 to 5 years, Lewis' data storage requirements are anticipated to grow by 5 to 10 terabytes. For the data to be readily available and capable of wide dissemination to the general user community, a highly integrated mass storage hierarchy is essential. Research is now being conducted to develop an integrated mass storage architecture.

In summary, CSD has a wide range of functions. Another service provided is mathematical consultation to scientists throughout Lewis. Other than the programming and computing services provided daily, the division is always looking ahead to provide the best technical services needed.

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Lewis Research Academy

Internal Fluid Mechanics

Boundary Layer Transition Explained

The prediction of boundary layer transition is one of the major unresolved issues in aircraft design. Experimentalists usually study this phenomenon by artificially exciting their flows with relatively two-dimensional, small-amplitude, single-frequency excitation devices, such as a vibrating ribbon or an acoustic speaker. The resulting initial disturbances are well described by linear stability theory, and at the low Mach numbers at which most of the experiments have been carried out are nearly two dimensional. This two-dimensional linear behavior can persist over very long streamwise distances when the excitation levels are sufficiently small, but the disturbance usually becomes three dimensional and nonlinear at sufficiently large downstream distances. Most experiments are carried out on a thin, flat plate carefully aligned with the upstream flow.

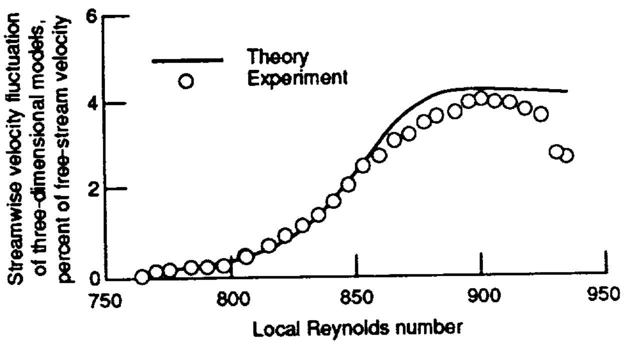
The linear regime is reasonably well understood. However, there is an important unresolved issue that involves the observed linear instability wave growth which occurs upstream of the theoretical (i.e., two-dimensional flat plate) lower branch of the neutral stability curve in some experiments. Work at NASA Lewis provides a possible explanation of this phenomenon. It shows that small but steady variations in the upstream vorticity field can produce significant (i.e., first order) variations in the streamwise velocity profiles within the boundary layer. These variations can, in turn, support instability wave growth upstream of the theoretical lower branch. Two limiting cases have been considered.

In the first case, the upstream vorticity field is entirely in the streamwise direction so that there is little or no vortex stretching outside the viscous boundary layer on the plate surface. The streamwise velocity profiles can then become inflectional within this boundary layer and can therefore support rapidly growing inviscid instabilities. These instabilities can exhibit spatial growth upstream of the lower branch of the ideal neutral stability curve.

In the second case, the upstream vorticity field is perpendicular to the plane of the plate. There is then considerable vortex stretching in the external inviscid flow. The resulting boundary layer profiles turn out to be noninflectional and therefore incapable of supporting the rapidly growing inviscid instabilities. However, the local wall shear becomes small (actually vanishes) at certain spanwise locations, and this tends to move the lower branch of the neutral stability curve upstream of the ideal location for the two-dimensional, flat-plate boundary layer.

The calculated velocity profiles show that there is a localized thickening of the boundary layer near the singular points where the wall shear stress vanishes. There is also a dramatic local increase in the transverse velocity component, which might produce a kind of "bursting phenomenon." This could then lead to a local transition of the boundary layer that bypasses the usual transition process.

The remainder of the work concentrates on the nonlinear stage of development. The first experimentally observed nonlinear stage is associated with the appearance of more or less periodic spanwise structures in the flow (peak-valley splitting, etc.). These spanwise structures are probably due to a resonant triad interaction between a pair of oblique subharmonic modes and a basic fundamental two-dimensional mode. A completely rational asymptotic analysis of this phenomenon has been carried out. It shows that the nonlinearity becomes important at very small instability wave amplitudes and that there is no backreaction of the oblique modes on the two-dimensional mode until the oblique modes become very large. This allows new, previously unanticipated effects to come into play before the backreaction has a significant



Comparison with experimental data of Corke and Mangano (ref. 1); frequency parameter, 82.7 x 10⁻⁶

impact on the instability wave growth. These effects play an important role in instability wave development and cause adverse-pressure-gradient boundary layers to behave very differently from the flat-plate boundary layer usually observed in the laboratory.

The analytical predictions are in excellent agreement with flat-plate boundary layer experiments and, unlike previous analyses, are able to explain the experimentally observed saturation phenomena that appear in these experiments.

Reference

1. Corke, T.C.; and Mangano, R.A.: Resonant Growth of Three-Dimensional Modes in Transitioning Blasius Boundary Layers. J. Fluid Mech., vol. 209, Dec. 1989, pp. 93–150.

Lewis contacts: Dr. Marvin E. Goldstein, (216) 433-5825; and Dr. Reda R. Mankbadi, (216) 433-8569

Headquarters program office: OAET

Computational Aeroacoustics Program Being Developed

All jet noise computations tend to be highly empirical. The only way to avoid this empiricism would be to solve the full time-accurate, compressible Navier-Stokes equations—a task that is well beyond current computational capabilities at the high Reynolds numbers of interest in engineering applications. A good compromise would be to use subgrid scale modeling (also called large-eddy simulation) to model the small turbulent scales that do not directly radiate sound and therefore do not have to be determined with great accuracy.

The acoustically active scales can then be determined by direct numerical computation. This leads to a computationally feasible problem that can accurately simulate the sound field and still be compatible with existing computers. NASA Lewis is working to develop the relevant large-eddy-simulation computer program. The relevant subgrid scale-modeling techniques have been highly developed over the past decade and can easily be adapted to our aeroacoustic application.

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Headquarters program office: OAET

Turbulent Mixing Studied

The mixing of two streams is of considerable practical interest in the development of a high-speed commercial transport, since the most promising noise reduction schemes rely on rapidly mixing out the jet exhaust velocity.

NASA Lewis is studying the flow over a splitter plate with a nominally uniform velocity on one side and zero velocity on the other. A very weak streamwise vorticity field is superimposed on the uniform flow. This weak vorticity field ultimately produces significant (i.e., first order) variations in the streamwise velocity profiles within the shear layer that forms downstream of the splitter-plate trailing edge. These velocity profiles are highly unstable and can support rapidly growing instability waves that ultimately lead to very efficient mixing of the flow.

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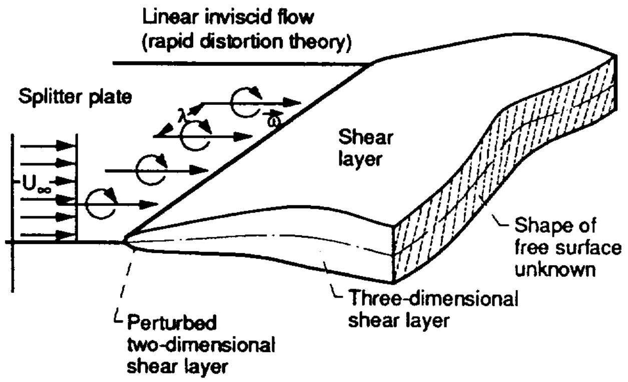

Turbulent flow over a splitter plate.

Turbomachinery Flow Modeled

A mathematical analysis has yielded a set of equations governing the conceptual flow model currently used to design turbomachinery blading. These equations govern the time-averaged flow state within a typical passage of a blade row embedded in a multistage configuration. This mathematical exercise has been transformed into a number of computer simulation models and has aided in the formulation of two turbomachinery research programs. The first research program is focused on advancing our understanding of the flow phenomena that affect the performance and life of multistage compressor blading. This research effort integrates computational fluid dynamics, flow modeling, and experimental fluid mechanics to develop flow models that designers can apply to advanced blading. Both university and industrial researchers have been and will continue to be active participants in this program.

The second research program will examine the control of secondary flow structures within low-aspect-ratio multistage turbines. A viscous multistage code developed at NASA Lewis will be used in this study.

This code has been used to identify the secondary vorticity field within the fuel pump turbine designed by Pratt & Whitney for the space shuttle main engine. The simulation revealed the strong influence of the rotor tip clearance on the secondary vorticity field and the impact of this field on the performance of the downstream stator.

A version of the multistage viscous code has also been rewritten to take advantage of the multiprocessor computing power of the Cray Y/MP. By exploiting the parallelism inherent in the three-dimensional multistage flow model, a simulation of a high-speed, four-stage axial flow compressor was executed at a sustained speed of over 1.5 gigaFLOPS. This simulation, which is the first of its kind, has received an award from Cray Research. Two builds and a total of five operating points were run. The simulation revealed the performance mismatch of the first-build rotors and substantiated the improvements made in the second build. Had this flow model been available to the designers, it would have indicated the shortcomings of the original build of the compressor and caused the design to be altered. The savings in time and money would have been considerable.

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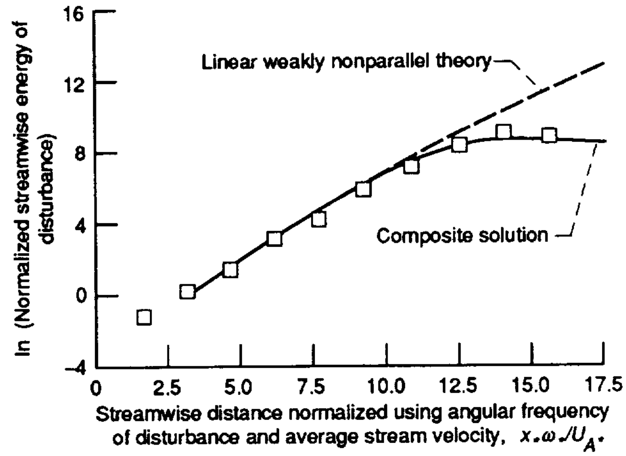
Control of Free Shear Flows

Considerable technological interest exists in using small-amplitude excitation for controlling mixing in free shear layers. A combination of numerical and asymptotic methods is used to analyze the nonlinear (spatial) evolution and rollup of disturbances evolving from strictly linear, finite-growth-rate instability waves on a weakly nonparallel free shear layer. The objective is to fully understand the dynamics so that ultimately effective means of mixing control can be developed. A composite expansion technique is used to obtain a solution that accounts for both shear layer spreading and nonlinear critical layer effects.

External forcing produces spatially growing instability waves that are initially governed by linear dynamics if the excitation amplitude is sufficiently small. Although the instability wave amplitude continues to increase in the downstream direction, its local growth rate must ultimately decrease owing to viscous spreading of the mean shear layer and nonlinear effects. The latter first become important in the critical layer. For the two-dimensional incompressible case the flow in the critical layer is governed by a nonlinear vorticity equation, and the instability wave amplitude is completely controlled by the nonlinear dynamics of the critical layer. The numerical results show that, owing to the continued rollup of the vorticity, even weak viscous effects convert the initial exponential growth to an algebraic one and cause the emergence of a quasi-equilibrium critical layer. The asymptotic structure of this stage has been obtained and used to infer the scaling for the next stage of evolution. In this stage the instability wave growth is simultaneously affected by mean flow divergence and nonlinear critical-layer effects and is eventually converted to decay. This final stage has been incorporated into the composite solution, which accounts for both mean-flow spreading and nonlinear effects.

A first-principle comparison with the experimental results of Thomas and Chu (ref. 1) has been carried out. The equivalent nonlinear parameters and the equivalent nonlinear streamwise coordinate as functions of the streamwise location were evaluated from a weakly nonparallel linear stability calculation. The (undisturbed) mean flow for that calculation was computed with the measured mean streamwise velocity profile at the first measuring station as an initial condition. The nonlinear effects are expressed in terms of a universal correction factor, which was evaluated by then solving the nonequilibrium nonlinear critical-layer problem. The results obtained by using this uniformly valid composite solution technique, which accounts for both mean-flow spreading and nonlinear effects, show excellent agreement with the experimental findings.

The success of single-frequency excitations in controlling shear flows has motivated several multifrequency excitation experiments focusing on better control of the flow signature. In such attempts, one- or two-frequency excitation amplified several instability waves, not only at the imposed frequencies but also at other frequencies as



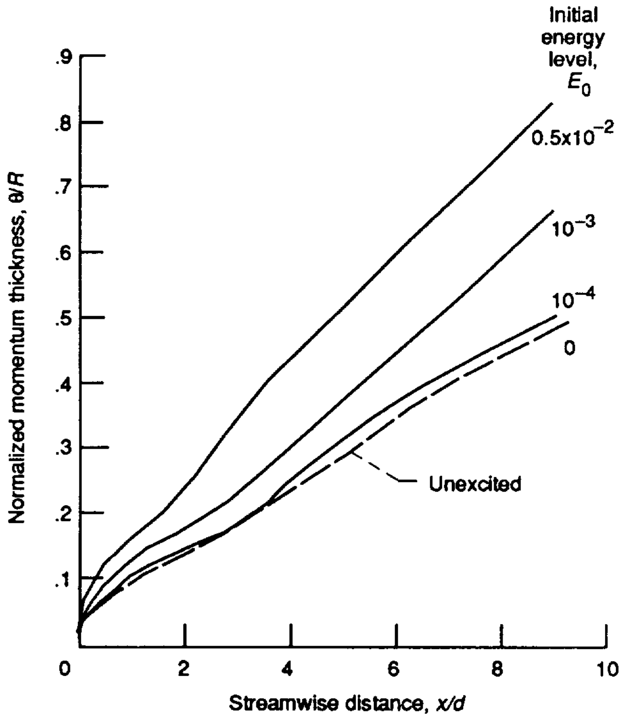
Comparison of composite solution accounting for both nonlinear critical-layer effects and viscous mean-flow spreading with instability-wave energy data from Thomas and Chu's (ref. 1) plane-jet shear-layer experiment.

well. To understand the mechanisms involved, a model is needed that accounts for the presence and interactions of several instability waves.

The integral energy approach was adopted to study multifrequency excited jets. The nonlinear development of the instability waves is governed by their wave-wave interactions, as well as by their interactions with the mean flow and the background turbulence. The initial amplitudes can be as large as those used in experiments attempting to achieve maximum control.

The analysis indicates that two axisymmetric modes at different frequencies can interact with other axisymmetric background modes and thereby amplify an enormous number of other frequencies. However, two modes at different frequencies with the same nonzero azimuthal wave number cannot, by themselves, amplify other frequency components. But a combination of axisymmetric and nonaxisymmetric modes at different frequencies can amplify other frequencies.

The results of this analysis explain several experimental observations, such as the dependence of the interactions on the initial phase difference between the waves and the excitation produced and the enhancement of the momentum thickness and the background turbulence. The increase in the spreading



Effect of initial excitation level on momentum thickness of a round jet.

rate was found to result from the turbulence enhancement rather than simply from the amplification of the forced stability waves. The high-frequency waves enhance the turbulence close to the jet exit, while the low-frequency waves are most effective farther downstream. The analysis not only successfully models and explains excited jets, but also provides a better understanding for the latter stages of the laminar-turbulent transition.

Reference

1. Thomas, F.O.; and Chu, M.C.: An Experimental Investigation of the Transition of a Planar Jet—Subharmonic Suppression and Upstream Feedback. Phys. Fluids A, vol. 1, no. 9, Sept. 1989, pp. 1566–1587.

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Characterization of Turbulence Continues

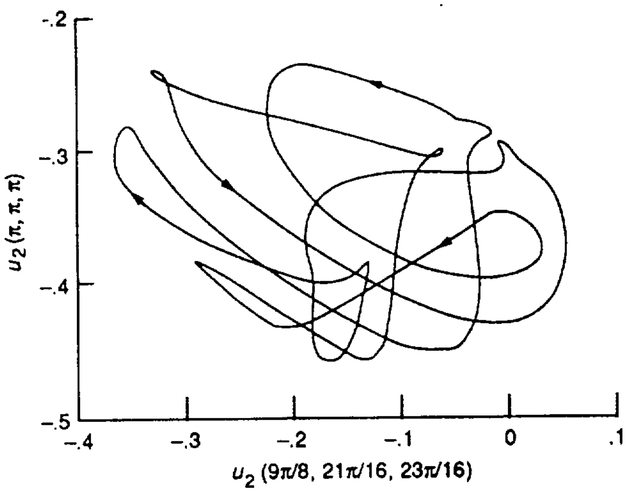
Fluid flows occurring in nature and in man-made fluid systems are usually turbulent. In spite of its pervasiveness, turbulence is still not well understood. Much of our inability to predict fluid flows stems from that lack of understanding.

NASA Lewis is working to characterize fluid turbulence and has numerically obtained turbulent solutions of the equations of fluid motion. We have determined that the nonlinear terms in the equations have a randomizing effect and that the solutions are chaotic in the sense that the instantaneous values are extremely sensitive to small changes in initial conditions.

However, sensitive dependence on initial conditions (chaoticity) appears not to be a sufficient condition for a flow to be characterized as turbulent. Some of our low-Reynolds-number flows show sensitive dependence on initial conditions, but their Poincaré sections (obtained by plotting the points where a flow pierces a plane in phase space) have a pattern in some of their parts. On the other hand, solutions at somewhat higher Reynolds numbers show a complete lack of pattern. It is suggested that one should reserve the term "turbulent" for flows that have sensitive dependence on initial conditions and, in addition, have Poincaré sections without pattern.

Another characteristic of turbulence is that it is aperiodic or nonperiodic in time. To better understand what turbulence is and is not, in that respect, we contrasted it with periodic flows. We were able to obtain numerically some time-periodic solutions of the Navier-Stokes equations at Reynolds numbers lower than those for which turbulent flow can be sustained. In each case, the flow (periodic or chaotic) was sustained by a steady forcing term in the Navier-Stokes equations, and the Reynolds number was varied by changing the strength of the forcing.

First we obtained a simple periodic flow for which the orbit in phase space has a simple shape. Then by increasing the Reynolds number slightly, we obtained the much more complex periodic flow shown in the figure, where a velocity component at one point in the flow is plotted against a component at another point. Because of the flow's complexity one might at first glance mistake it for a turbulent



Complex periodic flow.

or chaotic flow. However, the flow is definitely periodic, since it traces the same curve over and over. The flow appears to have an exceptionally good memory in being able to do that. By way of contrast, if the flow were turbulent, the curve would not repeat, but the region occupied by the trajectory would continue to get blacker as the running time increased.

We are continuing to search for additional periodic and chaotic solutions by varying the Reynolds number (or the strength of the forcing). In this way, we hope to obtain a better characterization of turbulence and a delineation of the routes to turbulence.

Bibliography

Deissler, R.G.: Characterization of Turbulence. Annual Report 1988, NASA TM-100925, p. 15.

Deissler, R.G.: Is Navier-Stokes Turbulence Chaotic? Phys. Fluids, vol. 29, 1986, pp. 1453–1457.

Deissler, R.G.: On the Nature of Navier-Stokes Turbulence. NASA TM-101983, 1989.

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Materials

Fundamental Properties of Solids and Interfaces

Current theoretical research is directed toward the development of semiempirical techniques that simplify prediction of the properties of solids and interfaces yet give quantitatively accurate results. These approaches involve the extension of universality in binding energy relations and the equation of state for solids.

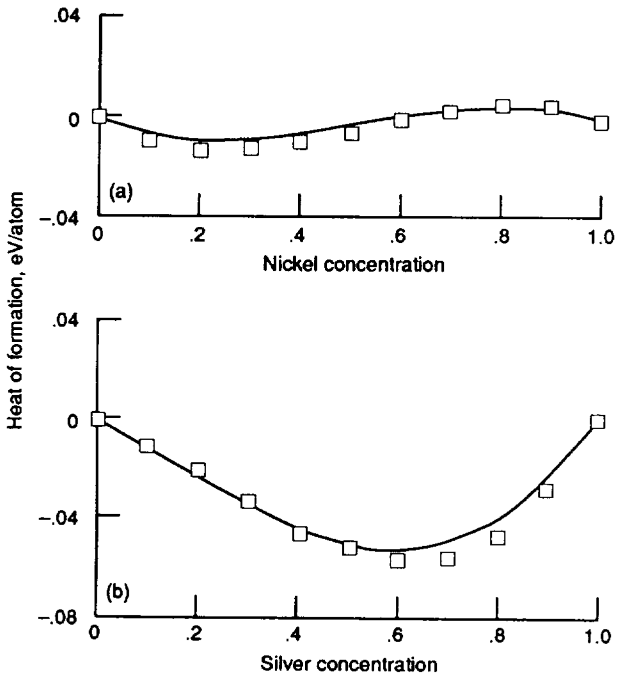
Progress has been made in discovering a universal equation of state for Van der Waals, ionic, covalent, and metallically bonded solids. These results have been applied to predicting the isothermal temperature dependence of the bulk modulus and its derivatives and the thermal expansion for all classes of solids. Also, the relationships between all the most widely used heuristic equations of state have been established. Some preliminary work is being performed in examining phase changes. The grain boundary studies involve implementing and improving on some new techniques—the equivalent crystal theory and the embedded atom method—for calculating energies, including the main-body interactions.

The equivalent crystal theory (ECT) is presently being used to study adhesion, shear, and the atomic force microscope. ECT is also being extended to alloys and to include angle-dependent terms in covalent solids. Considerable success has been achieved in predicting heats of transition of binary alloys.

Universality is being generalized to cases with charge transfer for diatomics, with the hope that it can be applied to solids, such as ceramics and metal-ceramic interfaces. Fully quantum mechanical calculations by the linear muffin-tin orbital method are being used in the development and as a test of these semiempirical techniques.

Bibliography

Hultgren, R., et al.: Selected Values of the Thermodynamic Properties of Binary Alloys. American Society for Metals, Metals Park, OH, 1973.



(a) Nickel-palladium.
(b) Silver-palladium.

Heats of formation as function of concentration (typical results).

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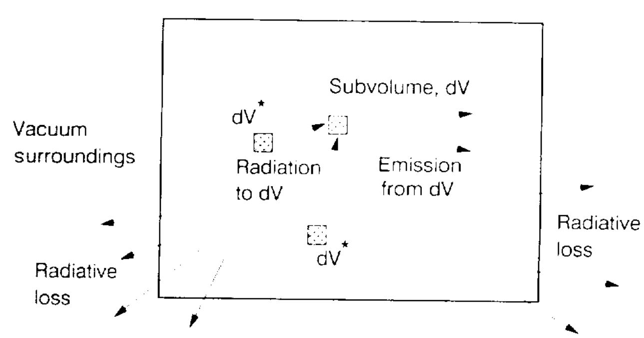
Radiation Heat Transfer Modeled in Semitransparent Materials

In some solid materials heat transfer can occur by the internal passage of infrared and visible radiant energy. This energy transfer is in addition to conduction and can be appreciable when temperatures are elevated and materials are partially transparent to these types of radiant energy. Radiant transfer can have a significant effect on the internal temperatures of windows used for viewing into experimental furnaces and combustion chambers. Ceramic coatings and engine parts, and some heat storage materials such as lithium fluoride, are partially transparent to radiative transfer. This is also true of some crystals that are to be grown in microgravity experiments, so that radiation influences the growth processes. Analytical and numerical research is being done at NASA Lewis to develop improved methods for modeling heat transfer in semitransparent materials. Predictions of local temperatures and heat flows within the material are desired. This work is a continuing effort.

Steady and transient heating processes have been investigated for combined radiation and heat conduction in plane layers and in geometries with square and rectangular cross sections. The materials partially absorb, emit, and scatter internal radiant energy. The surfaces can be heated or cooled by convection, and radiant energy passes through the surfaces going to or from the interior of the material. If the material is cooling in a vacuum, the only means for energy dissipation is by radiation from within the material out through the boundaries. The solutions yield detailed temperature distributions that can be used to evaluate cooling performance and to perform thermal stress calculations.

An alternating direction implicit method has been used to obtain transient temperature distributions and heat flows for radiative cooling of a square region with constant properties. Plane layers are currently under investigation in which transmission and absorption depend on the frequency of the radiation. Windows usually have frequency regions that are quite transparent and other regions that are more highly absorbing. A two-band model is being used with a different absorption behavior in each band. Internal heat conduction and interface reflections are included.



Transient radiative cooling of a rectangular semitransparent region in vacuum.

Bibliography

Siegel, R.: Finite Difference Solution for Transient Cooling of a Radiating and Conducting Semitransparent Layer. J. Thermophys. Heat Trans., vol. 5, 1991.

Siegel, R: Emittance Bounds for Transient Radiative Cooling of a Scattering Rectangular Region. J. Thermophys. Heat Trans., vol. 4, no. 1, Jan. 1990, pp. 106–114.

Siegel, R.; and Molls, F.B.: Finite Difference Solution for Transient Radiative Cooling of a Conducting Semitransparent Square Region. Submitted to Int. J. Heat Mass Trans., 1990.

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